Soviet Development of Gyrotrons

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PREFACE

This report was prepared in the course of a study of Soviet research and development of high-current, high-energy, charged particle beams and their scientific and technological applications. It is a part of an ongoing Rand project, sponsored by the Defense Advanced Research Projects Agency, which undertakes the systematic coverage of selected areas of science and technology in the USSR as reflected in the Soviet technical literature.

The report surveys the development of high-power cyclotron resonance masers and gyrotrons in the Soviet Union. Two related Rand reports in this area have been published by the present author: *Soviet Research on Crystal Channeling of Charged Particle Beams*, R-3224-ARPA, January 1985, and *Soviet Free-Electron Laser Research*, R-3259-ARPA, February 1985.

This study is intended for specialists in high-power microwave research, U.S. government decisionmakers concerned with advanced technology problems, and students of Soviet science and technology.

SUMMARY

During the period of gyrotron development in the USSR, its experimentalists progressed from a 3 kW 2 cm gyrotron in 1966 to a series of gyrotrons in the 1980s capable of operating at wavelengths as short as 0.6 mm at 100 kW and 2.8 mm at 30 MW, and including a plasma-filled gyrotron generating 90 MW in the centimeter wavelength range, and an autoresonant synchrotron maser hybrid for 20 MW at a 5 mm wavelength.

These results were obtained in the course of what appears to be a long-range systematic R&D program emphasizing high microwave pulse energy and continuous-wave power, and stable single-mode operation of large cavities. The implied combination of high output energy, monochromaticity, and coherence is useful in such practical applications as advanced search and pulse Doppler radars. The thrust of the program is the wavelength range from 0.1 to 10 mm which, according to Soviet authors, is not attainable at high power levels by either conventional microwave devices or lasers, but seems to be the natural domain of fast-wave structures used in the cyclotron resonance maser (CRM), the cyclotron autoresonance maser (CARM), and the gyrotron. Soviet authors note radar, communications, controlled fusion, plasma chemistry, and spectroscopy as possible applications of these devices.

The CRM, CARM, and gyrotron work has been concentrated at two research facilities, the Institute of Applied Physics (IPF) in Gor'kiy and the Lebedev Physics Institute (FIAN) in Moscow. The Institute of Nuclear Physics in Tomsk provided some accelerator technology support and expertise. The research issues pursued at these institutes included single-mode and second-harmonic operation, the effect of space charge on high-current performance of CRM, ion neutralization of electron beams, cavity shaping, studies of mode stability in high-power, large-cavity gyrotrons, and the development of millimeter wavelength gyrotrons capable of mode selection and high current transport. A significant achievement has been the development of CARM oscillators using Bragg mirror cavities.

For high-power gyrotrons driven by intense relativistic electron beams (IREB), diagnostics techniques for the display of IREB input and microwave output radiation were developed using mylar film luminescence.

In the belief that IREB-driven vacuum devices are approaching their theoretical limits, FIAN researchers have mounted a substantial program for the development of plasma-filled devices offering the promise

of transcending the power limits of vacuum-based technology. That endeavor is based on the considerable past research in plasma dynamics and high-current beam-plasma interaction performed by M. S. Rabinovich and A. A. Rukhadze, leaders of the gyrotron research at FIAN.

The development of IREB technology for high-power microwave applications has been the fastest rising sector of pulsed power R&D, a subject of intense and systematic development in the USSR for the past two decades, indicating the importance assigned by Soviet scientific leadership to CRM and gyrotron research.

The publications reporting this research fail to cover several significant issues, such as gyrotron amplifiers and the continuous-wave regime, suggestive of extensive classification of this research in the USSR. This impression is further strengthened by the drop in the frequency of publications in this field, apparent since the mid-1970s, accompanied by a rise in the number of research personnel active in the field each year of the same period.

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I. INTRODUCTION

Soviet researchers have been emphasizing their interest in the microwave frequency band around 300 GHz at GW to TW power levels where conventional oscillators and amplifiers are not practical. This high-frequency, high-power microwave region is said by Soviet authors to be useful in radar, communications, controlled fusion, plasma chemistry, spectroscopy, and other applications that warrant a strenuous effort to develop new technology with the necessary output parameters. Such a technology would be based on intense relativistic electron beams (IREB) driving stable cavities generating monochromatic coherent radiation. The foremost developer of advanced Soviet microwave technology, A. V. Gaponov, and his research organization, the Institute of Applied Physics (IPF) in Gor'kiy, have been engaged for many years in building devices capable of approaching these aims. Much of this work consisted of developing microwave oscillators and amplifiers based on slow-wave structures and the Cherenkov effect, which have by now reached GW powers and centimeter wavelengths. However, Gaponov believes that the millimeter and submillimeter wavelength range at MW and GW power levels is the natural domain of fast-wave structures utilizing the cyclotron resonance maser (CRM) effect, whose typical representatives are the cyclotron autoresonance maser (CARM) and the gyrotron. During the past decade, Gaponov and his co-workers at IPF, as well as a group of researchers at the Lebedev Physics Institute (FIAN) in Moscow, have been devoting part of their time to developing the CRM technology.

Soviet open-source publication statistics indicate that the development of IREB technology for high-power microwave applications has been the fastest rising sector of what is known as pulsed power R&D, a technological infrastructure essential to the development of controlled fusion reactors and directed energy projects. In turn, pulsed power has been for the past two decades the subject of intense and systematic development in the USSR, involving a substantial number of leading research institutes of the Soviet Academy of Sciences and of the State Atomic Energy Committee. The prominence of the IREB-driven high-power microwave research sector in the pulsed power field testifies to the extraordinary importance that appears to be ascribed to this sector by Soviet leadership.

This report presents a detailed account of Soviet CRM development based on Soviet open-source literature. Parts of this literature are well

known to U.S. researchers, and excellent reviews of Soviet gyrotron work have been published by such leaders of U.S. microwave research as V. L. Granatstein, J. L. Hirshfield, R. S. Symons, and H. R. Jory. The purpose of the present report is to trace Soviet developments through 1984, and to show Soviet results in the light of their historical development, and, most important, in the context of their organization, teamwork, leadership, timing, and research objectives. The report does not cover the extensive literature on slow-wave Cherenkov devices, and is limited to the CRM and gyrotron area. Neither does it deal with the details of practical applications of these devices. At high frequencies and high output power levels involving the use of high-current relativistic electron accelerators, considerations of size and weight impose severe limits on the applicability of these devices in situations demanding portability. These aspects of CRM and gyrotrons are not addressed in the available literature.

The first two sections of this report deal with the nature and history, respectively, of relativistic CRM devices. The historical account is limited to Soviet developments, while in some cases Western achievements are noted for comparison only. Much of this material is based on U.S. and Soviet reviews, with particular attention paid to Soviet assessments, concepts, and objectives of the research. Tables showing the classification of CRM devices and the chronology of Soviet experiments supplement the text.

Section III provides a sequence of the most important issues of gyrotron R&D as perceived by Soviet authors; it does not necessarily reflect Western views of this subject. Thus, the sequence has been assembled from issues that appear most frequently in Soviet technical reports, or that have been explicitly stated there as the most important.

Sections IV and V deal with individual Soviet research groups, the basic organizational units responsible for the CRM and gyrotron R&D. An outline of the leadership, personnel, organization, and historical development of these groups is followed by an account of each group's research activity and objectives.

The section on conclusions is followed by two appendices. Appendix A presents a verbatim text of the several patent applications on which the Soviet gyrotron development is based, and Appendix B provides the parameters of Soviet CRM and gyrotron experiments.

II. NATURE OF RELATIVISTIC CYCLOTRON RESONANCE DEVICES

The millimeter and submillimeter wavelength range of coherent electromagnetic radiation is difficult to span at high power levels. Much shorter wavelengths are the domain of lasers whose efficiency falls off with decreasing energy of the emitted quanta (increasing wavelengths). Longer wavelengths are the domain of conventional microwave devices; their power and efficiency also decrease as they approach the millimeter-submillimeter wavelength range due to the miniaturization requirement and to ohmic losses in the walls of the electrodynamic system.

In this situation, cyclotron resonance masers (CRM), representing microwave oscillators and amplifiers utilizing stimulated cyclotron radiation from electrons, offer the best promise of spanning the millimeter range at high power levels, since they combine the advantages of lasers (open, spatially developed electrodynamic systems), with those of microwave devices (emission of a large number of quanta by individual electrons) [1].

In the CRM, electromagnetic waves in a cavity or waveguide phase-bunch an electron beam in which the individual electrons move along helical orbits in the presence of an applied background magnetic field. Their frequency of operation depends on both, the resonance of the cavity frequency and the electron cyclotron frequency, the latter depending, in turn, on the magnetic field [2].

In principle, CRM can operate as sources of high-power microwave radiation at any electron energy. Since their operating frequency is fixed by the strength of the external magnetic field, they have better mode selectivity than conventional microwave sources, and are also effective in exciting higher modes, making it possible to increase the transverse dimensions of the electrodynamic system relative to wavelength and thus to handle high power at high frequency [3–7].

Microwave oscillators using stimulated bremsstrahlung of relativistic electrons are somewhat inferior to relativistic Cherenkov oscillators in terms of both power and efficiency. On the other hand, they cover a broader frequency spectrum, from 10 cm to a few microns [1].

Table 1 presents the classification of CRM devices in terms of the relations between phase velocity of electromagnetic wave, V_{em}, in the B_0 direction, axial velocity of the electron beam, V_b, and the velocity of light, c, as discussed in a Soviet source [8].

Table 1

CLASSIFICATION OF CRM

Velocity Relationship	Type of Device	Remarks
$V_{em} < V_b$	anomalous Doppler CRM	Capable of 100 percent efficiency, but more cumbersome than Cherenkov devices
$V_{em} > V_b$	normal Doppler CRM	
$V_{em} \sim c$	free-electron laser	Large Doppler shift, electron beam with low pitch factor and high current
$V_{em} = c$	cyclotron autoresonance maser (CARM)	Large Doppler shift, electron beam with low pitch factor and high current
$V_{em} > c.$	gyrotron	Negligible Doppler shift, electron beam with high pitch factor and relatively low current

The gyrotron, a variant of CRM, utilizes the effect of stimulated cyclotron radiation by monoenergetic electrons moving along the magnetic field lines in a helical trajectory. Gyrotrons are regarded by Soviet authors as "generators of high-power electromagnetic radiation in the millimeter wavelength range" [9].

The electron-optical system of the gyrotron forms a hollow electron beam with the electrons rotating at cyclotron frequency in crossed electric and magnetic fields of the injector. Forward motion of electrons in a rising magnetic field increases the rotational velocity of electrons. At the entrance to the cavity located in homogeneous magnetic field, the energy of cyclotron rotation exceeds several times the translation energy of the electrons. The electrons interact with the field of a weakly irregular waveguide at a quasi-critical frequency, making it possible to reduce the effect of velocity spread.

Since in the gyrotron, $k_z \ll k_\perp$, where k_z and $k_\perp$ are axial and transverse wave numbers respectively, its operating frequency is near the electron cyclotron frequency,

$$\omega = \Omega_0/\gamma + k_z v_z \sim \Omega_0/\gamma \quad ,$$

and the cavity is short in the axial direction.

Gyrotrons are designed for high average power as required in electron cyclotron resonance heating of magnetically confined plasmas in controlled fusion research, or for high peak power, one application of which is in driving high-energy linear accelerators. They may be based on a single cavity or may feature a complex resonator of two coupled cavities, allowing for higher modes with reduced ohmic losses and enhanced stability by virtue of the cavity-coupling effect. The single-cavity gyrotron can be modified by replacing the waveguide cavity with a Fabry-Perot etalon, resulting in a quasi-optical gyrotron. The potential advantages of the latter include improved mode control and natural separation between the microwave output path and the beam collector [1].

According to Soviet specialists, the gyrotron is the most successful microwave source of high-power radiation in the millimeter range because it is amenable to reliable mode selection and single-mode generation. Only in the gyrotron was the conversion of energy of the helical electron beam into electromagnetic radiation accomplished with adequate efficiency. The gyrotron is capable of forming intense electron beams with moderate electron velocity dispersion [3, 4, 10, 11, 12].

Another variant of CRM is the cyclotron auto-resonance maser (CARM). In the CARM, $k_z \gg k_\perp$. Therefore, the $k_z v_z$ term is large, denoting a Doppler frequency upshift, and the operating frequency is much higher than the electron cyclotron frequency. The cavity is long in the axial direction [6].

The Soviet developer of CARM, V. L. Bratman, considers it as a variant of the free-electron laser with Bragg mirrors, and a more promising IREB-driven source of millimeter and submillimeter wavelengths than the ubitron in terms of simplicity of energy pumping, electron beam quality requirements, and efficiency [13].

III. HISTORY OF SOVIET RELATIVISTIC CRM DEVICES

CRM devices were first proposed in 1959 separately by Schneider, Pantell, and Gaponov. In the USSR, these proposals were swiftly followed by construction and experimentation with CRM devices. In the next year, the Soviets reported an output power of up to 1 kW cw at 1 cm wavelength from TW-CRM and BWO-CRM in which trochoidal electron beams moved in crossed electric and magnetic fields.

These experiments with CRM were designed to study the interaction of helical and trochoidal electron beams with traveling electromagnetic waves in waveguides and the relative merits of the two beam modes. While it was obvious to Soviet researchers that helical beams focused by homogeneous magnetic field were superior to trochoidal beams, the early performance of the former was not satisfactory. In 1965, the output power of a CRM with a helical beam was significantly lower than that of a trochoidal CRM [14]. This was attributed to poor design of early helical CRM and lack of precise methods of analysis. Thus, according to Gaponov, Bott (1965) and Kulke (1969) used crude electron-optical systems. Gaponov used a single-mode waveguide for energy extraction mismatched to the cavity and obtained a higher power than Bott. The resulting output power of 200 W cw was nevertheless only 20 percent of the power transferred by the RF field from the beam [12, 14].

It was concluded that CRM devices were generally characterized by low efficiency and that a satisfactory efficiency of converting the energy of helical electron beams into electromagnetic radiation was possible only in the gyrotron. This was defined as a microwave oscillator or amplifier consisting of an adiabatic magnetron-type electron gun, capable of generating intense electron beams with moderate velocity spread, and a weakly irregular waveguide with a diffraction exit and a high degree of mode selection [12].

The advent of high-current relativistic electron beam technology has made it possible to improve significantly the performance of microwave devices because of several advantages of relativistic energy. First, the increasing mass of relativistic electrons reduces plasma frequency of the beam which, in turn, decreases the extent to which the beam perturbs the electrodynamic system and thus results in line narrowing of the output radiation. Second, in strongly relativistic beams, a decreasing electron energy has a negligible effect on electron velocity, so that a

high efficiency is maintained even in the presence of considerable losses, a fact of particular significance in Cherenkov devices. Third, rising energy for a given current increases the power of the beam, and thus the power of microwave devices driven by intense relativistic electron beams [15].

The development of gyrotron theory and effective realization of the gyrotron are credited to the Gor'kiy school of physicists headed by A. V. Gaponov. According to Gaponov and other Soviet researchers, as well as dates of patent applications, three stages are discernible in the Soviet development of gyrotrons, as shown in Table 2 [16].

The first stage began with discovery of two mechanisms of interaction between electrons gyrating in a static magnetic field and RF field of smooth waveguides and cavities. The first mechanism, based on electron bunching in RF magnetic or inhomogeneous RF electric fields (Gaponov, 1959), led to the early experiments with oscillators and amplifiers using helical electron beams (Pantell, Gaponov, 1959). The second mechanism, based on the relativistic effect, produced phase bunching of electrons [16].

Both mechanisms formed the basis of the classical theory of stimulated cyclotron radiation and the theory of CRM [17]. The linear and nonlinear theories of the interaction between helical and trochoidal electron beams and RF fields had been formulated in the mid-1960s. At the same time, experiments showed that a high-efficiency CRM was feasible [17, 18] and helped establish the basic principles of practical stimulated cyclotron radiation of helical electron beams in the millimeter and submillimeter wavelength ranges.

Table 2

CHRONOLOGY OF SOVIET CRM DEVELOPMENT

Stage	Period	Activity
1	1959–1964	Discovery and analysis of the CRM effect; formulation of linear and nonlinear theories. Early experiments.
2	1965–1974	Submission of basic patent applications (1967); construction of low-current, weakly relativistic gyrotrons; experiments in pursuit of higher output frequencies and efficiency.
3	1975–present	Application of high-current relativistic electron beams to gyrotrons and CARM.

The simplest method of creating nonequilibrium distribution of electrons in large volumes required the use of electron beams with tightly wound helical trajectories in good vacuum. In the experiments, such beams were generated by axially symmetric electron guns with conical cathodes. The smooth variation of electric and magnetic static fields in the gun and the drift space preserved the adiabatic ratio of the energy of electron rotation to electron gyrofrequency. The radiated power increased monotonically with increasing rotational and decreasing longitudinal electron velocities, and with increasing electron current. However, output power was limited by cooling problems and discharge in residual gas.

Further increases of total radiated power could be achieved by increasing the volume of the active medium (cross-section of the electron beam) which, in turn, called for quasi-optical open cavities [14]. High output power, expanded tunable frequency range in oscillators, and expanded bandwidth in amplifers called for the use of low-Q cavities [19].

Gyrotrons were first built during the second stage of CRM development by a group of Soviet researchers under Gaponov and M. I. Petelin. In 1967, this group submitted a series of patent applications for the gyrotron and its electron gun [20–24]. The patents were published in the official patent journal from five to nine years later, however, representing an unusually long delay by Soviet publication standards (see App. A for the complete patent texts).

The 1967 patents fall into three groups representing the oscillator, amplifier, and electron gun. While Gaponov in his 1980 review [16] referred to these patents as representing the gyrotron device, the patent applications themselves are limited to the term CRM.

The gyrotron oscillator was covered by a patent application with priority date of March 24, 1967. The application was entitled, "A device to generate electromagnetic oscillations in the centimeter, millimeter, and submillimeter wavelength range." The device was defined as a cyclotron resonance maser in which the entire structure from the cavity to the collector was a solid metal tube with a variable internal cross-section to increase efficiency and power. The claims of the patent covered variants of a transition section between the cavity and the output waveguide: a section with a supercritical narrowing to improve operating stability, a smooth transition section to increase the frequency tuning range, and a direct transition geometry in which the cavity cross-section smoothly increased to match the collector. The constant magnetic field at the cavity output end was specified as 60 to 85 percent of the field in the cavity proper [20].

The application for the gyrotron amplifier had a priority date of June 16, 1967, and was similarly entitled as "Amplifier of electromagnetic oscillations in the centimeter, millimeter, and submillimeter wavelength ranges." Gaponov's review called it the multicavity gyrotron-amplifier-gyroklystron. In the patent applications, it is called a multicavity CRM amplifier in which the electron cyclotron frequency or its harmonic is equal to the amplified signal frequency. The claims covered the basic solid metal tube structure and an axially symmetric electron gun for the hollow electron beam, whose radius was much larger than that of the helical electron trajectories to increase power and efficiency. The cavity was tuned mechanically using several telescopic metal tubes movable axially past each other. RF radiation absorbers were specified in the tubes to avoid exciting lower modes [22, 23].

The patent for a magnetron-type electron gun for cyclotron resonance masers concerned a cylindrical anode and cathode with an emitting strip. The main claim defined the ratio of cathode to electron beam diameters:

$$D_c/D_b = \beta \frac{(V_c V_{ac})^{1/2}}{V_a}$$

where D_c is the cathode diameter, D_b is the beam diameter, β is a numerical coefficient ranging from 1.7 to 2.2, V_c is the cavity potential, V_a is the anode potential, and V_{ac} is the critical voltage of the electron gun. The cathode potential is assumed to be zero. Another claim covered a protrusion on the anode near the outer boundary of the electron beam to remove electrons with excess oscillation energy [21].

The earliest reports on gyrotron experiments were delivered in 1966 to the Fifth Inter-University Conference of Microwave Electronics in Saratov. These reports covered the testing of gyrotrons operating close to cyclotron frequency and also to its second harmonic [25].

The early gyrotron builders were Gaponov and Petelin, as well as V. A. Gintsburg, A. L. Gol'denberg, D. P. Grigor'yev, L. V. Nikolayev, T. B. Pankratova, V. A. Flyagin, V. K. Yulpatov, G. N. Rapoport, and I. I. Antakov.

The early design of the gyrotron produced an output of several KW cw at the cyclotron frequency and its second harmonic, at first in the centimeter range, and then in long-millimeter, followed by short-millimeter wavelength, the last with the aid of a cryomagnetic solenoid. First experiments were also performed with the multicavity gyrotron-amplifier-gyroklystron described in the patent applications.

In the millimeter wavelength range, cw gyrotrons were at that time designed for wavelengths above 5 mm, while the range between 2 and 4 mm was covered only by gyrotrons with pulsed magnetic field.

The early experiments confirmed theoretical predictions that the gyrotron would be one of the most simple and reliable devices for high power levels in the microwave spectrum. The adiabatic magnetron-type injector electron gun provided the necessary helical beams. The open gyrotron cavity had good mode selection even with the relatively large cross-section of the order of wavelength squared. At the fundamental frequencies, adequate efficiency could be achieved even when the longitudinal velocity dispersion of the electron beam was of the order of average longitudinal velocity. The diffraction-type system of energy extraction from the cavity promoted mode selection, although at the cost of low-density power flux across the output window.

These advantages of the gyrotron induced Gaponov to propose gyrotrons as high-power coherent radiation sources in the cm, mm, and sub-mm ranges. Subsequent research was said to have justified this proposal [12, 25, 26].

By 1971, frequency-tunable gyrotron oscillators with a high-directivity of output radiation were developed [27]. The gyrotrons had split quasi-cylindrical cavities where tuning was effected by shifting mirrors and adjusting the magnetic field. The oscillators were used in high-resolution spectroscopy and to investigate nonlinear self-focusing of intense electromagnetic waves in plasma [28, 29].

In 1973, Petelin stated that the primary objective of this research was the generation of wavelengths shorter than 5 mm by cw or long-pulse gyrotrons. The problems with short-wave gyrotrons were RF power losses rising with frequency, and velocity spread in the electron beam produced by the adiabatic gun. Increasing frequency required an ever higher degree of surface finish of the cavity walls. At the same time, the then-current method of adiabatic gun design failed to take into account the effect of space charge on electron motion, so that the velocity spread in the electron beam severely limited efficiency for all currents exceeding 10 percent of the critical value. These effects were particularly aggravated in work with the second harmonic of the cyclotron frequency. The analysis of second-harmonic gyrotrons was reported to the Seventh Academic Conference on Microwave Electronics in 1972. A significant increase of efficiency of second-harmonic gyrotrons in the millimeter and submillimeter range was then considered possible only with high-current electron beams [26].

By 1974, computer codes were used in designing experimental gyrotrons [25] and attempts were made to eliminate parasitic oscillations in the high-current regime by the use of whispering gallery modes [30].

Table 3 illustrates the development of Gor'kiy gyrotrons from 1971 to 1978, in which the experimental data from a 1978 review by A. A. Andronov et al. [31] are shown alongside those from individual

experimental reports published in regular serials. The latter concern experiments performed under the leadership of N. I. Zaytsev et al. [26], Sh. Ye. Tsimring et al. [25, 32], N. F. Kovalev et al. [27], and L. V. Nikolayev et al. [33]. The years indicated in Table 3 are the earliest known dates associated with the publication of these experiments, in most cases marking the submission of the report to the editor.

The timing of these research milestones and key experiments cannot be determined precisely from Soviet accounts. While the dates discussed above have been derived either from publication data or from explicit statements of Soviet writers, the uncertainty involved may extend to several years. Table 3 is a case in point: In his review, Andronov presented the data as pertaining to 1978 gyrotrons at IPF, yet included two of Zaytsev's 1973 results of continuous-wave experiments. Similarly, Kovalev's 5 mm 10 kW gyrotron, reported in a 1974 publication, had been used in a plasma self-focusing experiment performed at NIRFI well before April 1971 [28].

The third stage, based on intense relativistic electron beams (IREB), was a major milestone in gyrotron development, as it was in the development of microwave devices in general. Rabinovich noted that the first high-current electron accelerators appeared in the United

Table 3

MILLIMETER AND SUBMILLIMETER GYROTRONS AT NIRFI-IPF IN THE 1970s

Continuous-Wave Operation

Item	1973 Zaytsev			1973 Tsimring	1978 Andronov review		
Wavelength	0.92 mm	1.91 mm	2.78 mm	8.9 mm	0.9 mm	2.0 mm	2.8 mm
Voltage	27 kV	18 kV	27 kV	19 kV	27 kV	40 kV	27 kV
Efficiency	6.2%	9.5%	31%	40%	6.2%	22%	31%
Harmonic	2	1	1	2	2	1	1
Power	1.5 kW	2.4 kW	12 kW	10 kW	1.5 kW	22 kW	12 kW

Pulsed Operation

Item	1971 Kovalev	1973 Zaytsev	1973 Nikolayev	1973 Tsimring	1976 Tsimring	1978 Andronov rev.	
Wavelength	5 mm	1.95 mm	1.2-2.2 mm	8.9 mm	8.9 mm	6.7 mm	3.0 mm
Voltage		26 kV	35 kV	26 kV	20 kV	65 kV	68 kV
Efficiency		15%	10%	43%	23%	35%	34%
Harmonic	1	2	1	2	2	1	1
Power	10 kW	7 kW	10-20 kW	30 kW	120 kW	1250 kW	1100 kW

States and the first attempts to use high-current electron beams in generating high-power microwave radiation were made in the United States in 1970. Thus, stimulated cyclotron radiation was observed in the earliest experiments with IREB propagating in smooth waveguides. In the United States, radiation power was enhanced by various pumping methods proposed by Friedman, Herndon, Hammer, Manheimer, Sprangle, Carmel, and Nation [34–36]. However, according to Rabinovich, these attempts were not sufficiently thought through and were, therefore, unsuccessful. For example, the efficiency of the first oscillators did not exceed 0.1 to 1 percent [37].

The first successful experiment in generating high-power microwaves with a high-current electron beam in a Cherenkov oscillator had been performed in 1973 at FIAN in a joint effort with NIRFI, yielding 500 MW at a wavelength of 3.1 cm with an efficiency of 15 percent. The output pulselength was 15 nsec. This experiment was repeated in the United States in 1974, with the same results, but with an efficiency of 17 percent [37].

High-power, high-current gyrotrons appeared in the literature in 1976. The first such gyrotron for vacuum operation was built by Didenko at IYaF in Tomsk [38]. Using an electron beam of 900 keV 8 kA 60 nsec pulselength, it produced an output power of 1.5 to 2 GW at 10 cm with a 30 nsec pulselength and an efficiency of 30 percent [37]. However, this experiment appears to have been an isolated effort, with no further gyrotron reports by the Tomsk institute forthcoming in the available literature.

IREB-driven megawatt gyrotrons and CARMs have been built by other Soviet groups in the subsequent years. In Gor'kiy, V. L. Bratman reached 30 MW at 2.8 mm wavelength in a vacuum gyrotron with an echelette cavity [39] and M. I. Krementsov and P. S. Strelkov of FIAN in Moscow obtained IREB-driven gyrotron powers of 25 MW at 7.5 mm wavelength [40].

An important parallel line of development of high-power gyrotrons has been the effort to use plasma-filled cavities as a means of avoiding the critical current limitation of vacuum devices. The theory of plasma electronics had been established by M. S. Rabinovich and A. A. Rukhadze at FIAN in the early 1970s, and experimental work had been continued there by Krementsov and Strelkov since 1973. In 1982, they reported obtaining 90 MW at 1.5 cm wavelength from plasma-filled devices [41].

In 1980, Gaponov set forth the following objectives for the further development of high-efficiency high-power gyrotrons: high-current density electron guns and stable single-mode operation of large cavities, reduction in the heat load imposed on the cavity and the output

window of the gyrotron, and gyrotron output of 2 to 3 mm at 1 MJ per pulse for applications in tokomaks and radar [16].

In 1983, a group of researchers at the Kurchatov Atomic Energy Institute used 200 kW gyrotrons operating at a wavelength of 3.6 mm in the T-10 tokomak controlled-fusion experiments. The gyrotrons delivered a pulselength of 0.15 sec, indicating a very long pulse capability [88].

A general outline of the chronology of Soviet gyrotron experiments is presented in Table 4 (which includes the material of Table 3 to preserve continuity).

Table 4

SOVIET CRM-GYROTRON EXPERIMENTS BY YEAR AND ATTRIBUTION

Year	Principal Investigator	Device	Wavelength	Power	Eff.	Remarks
1965	Gaponov, NIRFI	CRM	3.4 cm	6 W		
	Gaponov, NIRFI	CRM	1.2 cm	190 W		
1966	Gaponov, NIRFI	gyrotron	2.0 cm	3 kW	50%	
	Gaponov, NIRFI	gyrotron	1.2 cm	4.3 kW	18%	
1971	Kovalev, NIRFI	gyrotron	5 mm	10 kW		
1972	Gol'denberg, NIRFI	gyrotron	cm range	110 kW	45%	at 3.5 A
	Gol'denberg, NIRFI	gyrotron	2 cm	380 kW	45%	at 180 kW
1973	Nikolayev, NIRFI	gyrotron	1.2-2.2 mm	10-20 kW	10%	
	Tsimring, NIRFI	gyrotron	8.9 mm	10 kW	40%	
	Tsimring, NIRFI	gyrotron	8.9 mm	30 kW	43%	
	Tsimring, NIRFI	gyrotron	8.9 mm	120 kW	23%	
	Zaytsev, NIRFI	gyrotron	0.92 mm	1.5 kW	6.2%	cw
	Zaytsev, NIRFI	gyrotron	1.91 mm	2.4 kW	9.5%	cw
	Zaytsev, NIRFI	gyrotron	2.78 mm	12 kW	31%	cw
	Zaytsev, NIRFI	gyrotron	1.95 mm	7 kW	15%	
1975	Strelkov, FIAN	CRM	3 cm	2 MW	2%	plasma
1976	Didenko, IYaF-TPI	gyrotron	10 cm	2 GW	30%	
1978	Unattributed	gyrotron	2.0 mm	22 kW	22%	cw
	Unattributed	gyrotron	6.7 mm	1.25 MW	35%	
	Unattributed	gyrotron	3.0 mm	1.1 MW	34%	
	Strelkov, FIAN	gyrotron	3 cm	60 MW	15%	plasma
	Strelkov, FIAN	gyrotron	3 cm	25 MW	20%	
1982	Strelkov, FIAN	CRM	7.5 mm	23 MW	6%	at 0.5 kA
	Strelkov, FIAN	gyrotron	7.5 mm	25 MW		
	Strelkov, FIAN	CRM	1.5-4.6 cm	90 MW	21%	plasma
	Nusinovich, IPF	gyrotron	0.8 mm	120 kW	15%	
	Nusinovich, IPF	gyrotron	0.71 mm	80 kW		
	Nusinovich, IPF	gyrotron	0.6 mm	100 kW	8.2%	
	Bratman, IPF	CARM	4.3 mm	6 MW	4%	Bragg mirror
	Bratman, IPF	CARM	2.4 mm	10 MW	2%	Bragg mirror
1983	Strelkov, FIAN	gyrotron	7.5 mm	25 MW		
	Alikayev, IAE	gyrotron	3.6 mm	200 kW		long pulse
1984	Nusinovich, IPF	gyrotron	4 mm	156 kW	34.6%	
	Nusinovich, IPF	gyrotron	4 mm	212 kW	19%	
	Nusinovich, IPF	gyrotron	3.2 mm	300 kW	25%	
	Bratman, IPF	gyrotron	3.8 mm	20-30 MW	3%	
	Bratman, IPF	gyrotron	2.8, 3.4 mm	20-30 MW	1%	
	MGU	gyrotron	5 mm	20 MW		hybrid

IV. PRINCIPAL ISSUES OF SOVIET GYROTRON R&D

This section presents the issues involved in Soviet gyrotron R&D that appear to be the most significant to Soviet researchers and are discussed most frequently in their reports.

SINGLE-MODE OPERATION

A large size of the interaction space is necessary to reach high power in gyrotrons and other electron devices. However, for any given wavelength, large size calls for operation at high cavity modes with attendant instability due to mode competition. Different methods of mode selection were considered to provide a stable single-mode operation in gyrotrons.

An azimuthal mode selection by two-mirror resonators was proposed in the early stage of the research by L. A. Vaynshtein [42]. However, according to Nusinovich, this method decreased efficiency by disturbing the axial symmetry of the gyrotron interaction space [43].

Somewhat later, an axial mode selection by profiling open resonators was proposed by Vlasov et al. [44].

During the second stage of gyrotron development, Vlasov proposed a radial mode selection by coaxial resonators [45]. With this method, properly chosen radius of a thin hollow electron beam would introduce sufficient starting current differences among modes with different radial indices.

However, large interaction space enhances several modes even in highly selective resonators. When their amplitudes are large enough, the nonlinear properties of the electron beam induce mode competition.

At first, mode competition in a gyrotron was understood only in terms of a linear theory derived from the consideration of starting currents of the competing modes. It was soon discovered, however, that only an analysis of nonlinear mode interaction can answer the question of which particular mode or modes can be established in a given multimode oscillator. In 1973, Nusinovich laid the foundations of nonlinear analysis of multimode processes in gyrotrons [46].

An attempt to produce single-mode generation in large-volume gyrotrons was made by Strelkov and Krementsov in an experiment with a hollow electron beam of 300 to 400 kV, 0.1 to 2 kA, 30 nsec pulselength [4, 5, 47, 48].

A basic task in the attempt to achieve single-mode generation in high-power IREB-driven gyrotrons is to determine the actual radiation mode. Among the several methods available for this purpose and suitable for 50 to 1000 MW microwave devices, the most advanced is the method based on thin metal film capable of producing a sharp picture of spatial distribution of the emission during a pulse. It was used to obtain, for the first time, the mode composition of gyrotron radiation. The Terek-2 accelerator was used in conjunction with a gyrotron operating in the TE_{13} mode and delivering 0.3 J in a 20 nsec pulse at 7.5 mm with maximum power density of 4.5 MW/cm^2 [10, 49].

SECOND-HARMONIC OPERATION

Experimental results showed that unstable operation at the second harmonic of cyclotron frequency of a high-output-power gyrotron was due to competition of other modes and cyclotron-frequency traveling waves, in addition to self-excitation. The simultaneous suppression of all parasitic modes has increased the stability and output power significantly. The operation of gyrotrons at the second harmonic has made it possible to decrease the external magnetic field by a factor of 2 [17]. This was considered an advantage regardless of the advances achieved in superconducting solenoid technology by Zaytsev [26]. Other advantages of second harmonic were a lower thermal load on the collector, relaxed requirements for electron gun parameters, and higher beam current and cavity Q for optimum efficiency [32].

The first experimental gyrotrons operating at the second harmonic had efficiencies of 15 to 20 percent [25], which was far from the theoretical limit of 70 percent postulated in 1968 by Moiseyev, Rogacheva, and Yulpatov [50], and in 1972 by Nusinovich and Erm [51].

The theory of second-harmonic gyrotrons with optimized cavity RF field distribution was given by Moiseyev, Rogacheva, and Yulpatov in 1968. Both theory and experiments showed that peak efficiency of the second-harmonic gyrotron was close to that of gyrotrons operating at the fundamental. However, the former had a significantly lower frequency stability when output power was increased by increasing the beam power [32].

Parasitic modes were suppressed by either varying the axial distribution of the magnetic field or by using absorbing inserts, or both. A substantial shortening of the homogeneous region of the magnetic field had increased the transverse velocity of the beam. Thus the starting current of the TE_{021} working mode increased more than that of the TE_{21} traveling wave, resulting in a considerable drop in efficiency. The

absorbing insert in the cavity eliminated all parasitic modes except for the TE_{022} mode, which was excited at much higher beam currents. The combined shortened magentic field and absorber suppressed the TE_{21}, TE_{022}, and TE_{023} modes and increased stability at high-output power levels. An adiabatic magnetron-type electron gun was used in the gyrotron [32].

SUPERCONDUCTING AND PULSED MAGNETIC FIELD

CRM devices are the best candidates for the wavelength range of mm and sub-mm wavelengths where no other device can reach the output power of a CRM. To operate in this range of wavelengths, the CRM must have magnetic field intensities from several tens to several hundreds of kGauss. These fields were usually established with superconducting solenoids. Superconducting solenoids in short-wave gyrotrons proved to be convenient to work with and, mainly, were capable of cw generation. Their output power was 22 kW at 2 mm and 1.5 kW at 0.92 mm. However, the superconducting technique for large enough volumes was limited to field strengths of 100 to 150 kGauss, precluding submillimeter gyrotron operation. For example, the shortest wavelength obtained by Zaytsev from a gyrotron with superconducting solenoid was 0.92 mm [26].

A more promising method of operating gyrotrons in the submillimeter range involves the use of pulsed solenoids, as reported by J. B. Bott [52] and L. V. Nikolayev [33]. Nusinovich estimated that pulsed magnetic fields are feasible up to 300 kGauss [3, 9].

Superconducing magnets up to 170 kGauss are attractive for cw CRM or CRM with a high repetition rate. For single-pulse CRM, the most suitable are pulsed magnets, which are also cheaper and simpler to make and operate. Reproducible fields of pulsed magnets can reach 450 kGauss which, in principle, makes it possible to expand the CRM wavelength range up to 0.25 mm, using the fundamental frequency of cyclotron resonance, and up to 0.12 mm at the second harmonic of the gyrofrequency [33].

According to Nusinovich's recent report, gyrotrons with pulsed solenoids and stabilized energy storage delivered over 100 kW at up to 500 GHz and pulselengths of the order of 100 μsec [53].

IREB DEVELOPMENT

While efficient gyrotrons with weakly relativistic beams have been built, any significant increase in output power requires high-current relativistic beams. Much of the theory employed in Soviet IREB-driven gyrotron experiments has been developed by Bratman, Ginzburg, and Nusinovich [4, 5, 54].

The theoretical design of electron beams suitable for relativistic microwave devices has been performed by a group at IPF, including V. Ye. Nechayev and V. M. Sveshnikov, who use the KSI-BESM computer code to solve problems of high-current relativistic electron optics [55].

Significant progress in accelerator development has been achieved in Tomsk during the period from 1965 to 1975. An axially symmetric injector with cylindrical anode and cathode immersed in a homogeneous magnetic field ensured beam reproducibility from shot to shot in spite of continuous deformation of cathode surface due to explosive emission. The pulse repetition rate was brought up to 100 Hz, and the output power of coherent microwave radiation sources up to GW per pulse in single pulses [56].

The principal accelerator system employed at FIAN to provide a high-current relativistic electron beam in gyrotron experiments is the Terek-2, developed by the Institute of Atmospheric Optics in Tomsk for FIAN, some time prior to 1973.

The accelerator consists of an electron gun, high-voltage extractor of the accelerating voltage pulse, a Blumlein pulse-forming line, a pulsed auto- transformer, and a controlled high-voltage switch. The insulator is transformer oil. The accelerator has been designed for 550 keV, 10 kA, 30 nsec pulselength. Beam energy can be varied smoothly from 200 to 550 keV. The cold cathode operates in the explosive emission regime, voltage pulse risetime is about 8 nsec, and the Blumlein impedances are 10 and 15 ohms.

The accelerator design allows for beam injection into a quasi-stationary magnetic field without significant field perturbation. The acknowledged application of the Terek-2 accelerator is for the study of beam-plasma interaction [57].

The accelerator system used at IPF in the CARM experiments is the Neptun-2, providing a hollow electron beam of 500 to 600 keV, up to 7 kA, and 100 nsec pulselength [39]. This accelerator could have been derived from the Neptun machine developed prior to 1973 at the Kurchatov Institute of Atomic Energy. The Neptun had a water Blumlein line and two Marx generators in series. It delivered from 10.5 to 1 MeV, 10 to 30 kA, 40 nsec pulselength, and maximum current

density of 3 kA/cm^2. Its cathode service life was from 1000 to 2000 shots at 700 kV [58].

TRANSVERSE ELECTRON VELOCITY

According to Strelkov and Krementsov, the greatest difficulty in shortening the wavelength to the submillimeter range was encountered in the attempt to produce a hollow IREB with a transverse-to-axial velocity ratio approximately equal to unity [6].

In weakly relativistic CRM and gyrotrons, helical electron beams were normally produced by a magnetron-type gun and were adiabatically compressed by an increasing magnetic field. The conical hot cathode of such a gun carried a narrow oxide emitter strip. The electric field on the surface of the emitter was directed at an angle to the magnetic field, resulting in the same transverse-to-axial velocity ratio for all electrons in the beam. The angular divergence of the beam, caused by beam self-field distorting the electric field at the edges of the emitter, could be reduced to tolerable levels by decreasing beam current. However, this "classic" magnetron gun cannot be used to produce intense relativistic electron beams, for two reasons. First, since the IREB is obtained from explosive emission, and any conductor becomes an emitter in the course of explosive emission, an emitting strip on a conical cathode is no longer possible. Second, the space charge and the attendant electric-field distortion assume, in principle, a major role in explosive-emission cathodes, since it is the space charge that ultimately limits the total diode current.

The most promising pumping systems for relativistic devices depend on a non-adiabatic magnetron injector or on resonant acceleration of rectilinear beam particles in a combined spatially periodic and homogeneous magnetic field. In the non-adiabatic injector system, developed by Strelkov and Krementsov, a cylindrical cathode is immersed in the magnetic field of a solenoid whose internal surface serves as the anode. The electron beam is emitted only at the edge of the cathode, near its top surface, since the electric field at the top surface of the cathode is screened off by the beam space charge. Emerging from the diode, the electrons enter a region of sharply inhomogeneous magnetic field, where they are given transverse velocity. Beyond this region, the transverse velocity increases in an adiabatically increasing magnetic field induced by a second solenoid. This system yields a high-quality beam whose current equals the full diode current [40].

The method of combined field, developed by Bratman for the CARM-ubitron oscillator with Bragg mirrors [59, 60], provides for

modulating the field of a pulsed solenoid by a periodic array of thin rings. To avoid weakening the homogeneous field component by the screening action of the rings, the latter are provided with radial slits, or helical rings are used to form open conductors. If the skin layer is thin, the relatively thicker rings are immersed in the magnetic field as in an ideal fluid. The thicker the rings, the more effective is field modulation. As a result, the periodic field generated by currents flowing on the internal surfaces of the rings is much higher than the field due to currents on the external surfaces [61].

In mm wavelength systems, electron beams were obtained whose transverse velocity reached 0.4 c and had low velocity spread [61].

IRREGULAR WAVEGUIDE STRUCTURES

In CRM and gyrotron devices, the conducting body forming the anode, beam transport channel, and the interaction region, often has a variable cross-section. In designing pulsed electron beams propagating through such irregular waveguides, one must consider transient phenomena that can limit the maximum current and change the electron energy spectrum. A group of FIAN researchers, including A. A. Rukhadze, S. I. Krementsov, and M. D. Rayzer, performed a series of experiments with a hollow IREB in an irregular waveguide to test for perturbations in the beam structure [62].

The experiments involved the Terek-1 accelerator with a coaxial magnetic insulation diode delivering 670 keV, 5 kA. The axial magnetic field varied from 4 to 16 kGauss. The electron beam was allowed to propagate either through a 30 mm constant-diameter waveguide 300 mm long, or through a two-section waveguide consisting of a 100 mm long section, 30 mm in diameter, joined across a 60 mm transition cone to a 300 mm long section, 70 mm in diameter.

In the constant-diameter waveguide, the hollow beam structure remained unaffected for all values of the magnetic field from 5 to 12 kGauss. In the irregular waveguide, the beam was subject to azimuthal current density perturbations. The hollow beam expanded and became practically solid over a distance proportional to the axial magnetic field intensity. The authors concluded that the azimuthal perturbation instability of the hollow electron beam in irregular waveguides may significantly limit the peak current and change the current pulse delay and electron energy spectrum.

DIAGNOSTICS OF IREB AND MICROWAVE OUTPUT RADIATION

During the second stage of gyrotron development, the group of P. S. Strelkov and V. I. Krementsov has applied a new method of visualizing and measuring the electron beam current density distribution, beam radius and angular dispersion, and microwave output distribution in any perpendicular plane during each accelerator pulse. According to Strelkov, this was the most important development in the transition from centimeter to millimeter wavelength IREB-driven gyrotrons [48].

The previously used diagnostics for the electron beam and microwave radiation were no longer satisfactory. The standard diagnostics for IREB measurement, based on the use of thick dielectric or metal plates opaque to electrons, had a number of disadvantages, due mainly to the effect of measurement on the beam itself. The usual methods of identifying the oscillation mode were based on far-field power density distribution or on a large set of neon tubes in the plane of the antenna horn. However, the former failed to yield complete information on a single pulse, involved much work, and required high repeatability of output radiation pulses. The latter method yielded only a crude image of the power density distribution. In view of the enormous radiated power, single-shot operation of the oscillator, high level of parasitic electromagnetic fields, and pulse-to-pulse instability, a change in the traditional methods of radiation mode diagnostics was found necessary.

The new diagnostics involved the use of thin mylar films. In the case of the electron beam, the latter was allowed to pass through the mylar film, producing luminescence which was photographed or displayed on a television screen. The mylar film was coated with aluminum to prevent the light from accelerator diodes from darkening the photographic film. It was assumed that the intensity of luminescence of the mylar film was proportional to film thickness and beam current density without any threshold effect, if the mylar film thickness was much less than the electron mean free path in the material. The luminescent image thus represented the current density distribution in a given beam cross-section integrated over an electron beam pulse [63, 64].

For microwave radiation, two techniques were developed. The first provided a direct picture of film damage by the gyrotron radiation pulse. In the second, the film was a passive absorber of a display screen emission.

The first technique was based on the finding that the absorption of electromagnetic radiation in metal film that is thin relative to skin

layer can reach 50 percent in a broad range of wavelengths. The absorbed energy causes intense heating of the film that can be partially or completely vaporized, leaving the substrate intact. The vaporization of the metal film changes its transparency to visible light, resulting in a pattern of spatial distribution of electromagnetic radiation intensity in the film plane.

In the experiments, aluminum, silver, and gold films were used with coefficients of transmission of 3 to 70 percent and absorption of 25 to 50 percent. The metal was sputtered on a 5 μ mylar substrate. In the course of a radiation pulse, the damage took the form of strongly elongated regions, mostly oriented at right angles to the electric-field lines of force of the radiated mode. Thus, the observed picture provided additional information on the polarization structure of the field.

The second technique was designed for gyrotron radiation power below the threshold of metal film damage to provide a high-resolution pattern of spatial distribution of emission from a single pulse. The display screen was made of an absorbing metal film, similar to the above, deposited on a mylar substrate and coated with a layer of temperature-sensitive phosphor. The latter was excited by an external continuous UV source. Because of the interaction of the screen with the gyrotron radiation pulse, the phosphor was quenched to a higher extent in areas corresponding to higher intensity of incident radiation. The visual sensitivity threshold of the screen was about 1 mJ/cm^2, while the expected power density of the experimental gyrotron was 9 mJ/cm^2. Since the screen operation did not incur damage to the metal film, the screen could be used repeatedly [10, 63].

The display screen was the subject of two patent applications submitted by a FIAN group in 1970 and published in 1974 and 1978 (see App. A for complete texts of the patents).

The preliminary experiments with the thin-film diagnostics of IREB were completed in 1979. A 300 keV 400 to 2000 A electron beam was used in the experiments. The mylar film was 10 μ and the aluminum coating was 1 μ thick. Beam energy loss in passing through the film was estimated at about 1 percent, and the resulting electron divergence was about 4.5°. For 800 keV beams, the energy loss should be 0.3 percent and divergence 2°. The mylar film could be used repeatedly, if the current density did not exceed 2 kA/cm^2 for a 50 nsec pulselength [63].

In 1981, the new diagnostics were used in Strelkov's experiment with the 25 MW gyrotron (see p. 33).

V. ORGANIZATION OF SOVIET CRM AND GYROTRON R&D

Soviet work on CRM and gyrotrons is being performed by the same personnel engaged in the study of microwave devices based on the Cherenkov effect and employing slow-wave systems. The development of fast-wave technology has, so far, represented a relatively small share of the total workload of these people.

The CRM and gyrotron work has been primarily in the hands of researchers at the Radiophysics Institute (NIRFI), who were transferred in 1977 to the new Institute of Applied Physics (IPF), both at Gor'kiy. A similar effort has been pursued at the Lebedev Physics Institute (FIAN) in Moscow. The Gor'kiy and Moscow institutes have enjoyed a high degree of cooperation in this research and constitute practically the entire Soviet CRM and gyrotron R&D. Exceptions are a small effort at the Moscow State University (MGU) and Didenko's experiment performed at the Nuclear Physics Institute (IYaF- TPI) in Tomsk.

Soviet authors attribute the initiation of CRM and gyrotron research to A. V. Gaponov, director of IPF, who also supervised the work in the 1960s and early 1970s. After that time, however, Gaponov appears mainly as a consultant, rather than participant in the development of CRM and gyrotrons, and the role of overall operational leadership of this work at NIRFI and later at IPF has been assumed by M. I. Petelin. Petelin's supervisory role had also been occasionally acknowledged by the researchers in this area at FIAN. The equivalent overall supervision at FIAN is in the hands of A. A. Rukhadze and M. S. Rabinovich.

While the Soviet source materials do not contain explicit descriptions of the organization and detailed leadership structure of this R&D effort, the frequencies of coauthorships in the literature make it possible to discern the outlines of individual research groups, their variation over extended periods of time, and the apparent hierarchical relationships among the coauthors. Thus, there are one or two authors in each group who appear much more frequently than the rest; these are assumed to be the principal investigators. The frequencies of courtesy statements in the research reports also indicate supervisory individuals and make a distinction between scientists and technicians.

THE GOR'KIY GROUPS

The NIRFI and IPF researchers in the CRM and gyrotron area break down into three distinct groups whose personnel has remained fairly stable over the years. The histories of these groups show a fairly similar pattern. They have all been formed while still at NIRFI, the dates of their first appearance ranging from 1971 to 1974. Their initial research had been limited to theory, with experiments commencing a few years later. All three appear quite similar in size, as measured by number of personnel and publication frequency, and all are supervised by Petelin. In this report, the groups are identified by the assumed principal investigators, as follows:

1. Sh. Ye. Tsimring
2. G. S. Nusinovich
3. V. L. Bratman

These three groups are the descendants of a loose association of authors, led by Gaponov and Petelin at NIRFI, who performed the early gyrotron experiments with low-current, non-relativistic electron beams. Some of these authors became members of the three NIRFI-IPF gyrotron groups.

THE FIAN GROUPS

The equivalent research at FIAN has been performed by a large group pursuing two main objectives in the area of IREB-driven gyrotrons: the development of plasma-filled gyrotrons as a means of increasing the output power of the oscillator, and the development of the more conventional vacuum gyrotrons. While maintaining the same leadership and main core of experimentalists, each objective claims a different membership of theoreticians. Of the two, the plasma research subgroup has been larger and has been longer in existence. The FIAN group has been led by A. A. Rukhadze and M. S. Rabinovich, the principal investigators and experimentalists being P. S. Strelkov and M. I. Krementsov. There is evidence that Petelin of IPF also shares a supervisory role in the vacuum subgroup of FIAN.

VI. ACTIVITIES OF CRM-GYROTRON R&D GROUPS

Figure 1 shows the chronological outline of the R&D activity at Gor'kiy and FIAN. The early work presented in the figure under Petelin has been omitted from the following more detailed discussion of these groups.

THE GOR'KIY GROUPS

Tsimring's Group

Tsimring's group has been active since 1967 in theoretical work, with a relatively brief experimental period from 1973 to 1977 supervised by Petelin. The membership of the group includes V. K. Lygin, V. N. Manuilov, V. A. Varentsov, G. S. Korablev, D. V. Kisel', V. G. Pavelev, A. L. Gol'denberg, Ye. G. Avdoshin, L. V. Nikolayev, and I. N. Platonov. Its main areas of study are the effect of space charge on high-current performance of CRM and ion neutralization of electron beams and cavity shaping. Experimental devices included a gyrotron with parasitic mode absorber (120 kW at 8.9 mm).

Tsimring's theoretical work has been confined to the study of the effects of space charge and high current on the quality, mainly transverse velocity spread, of long helical electron beams used in gyrotrons.

The objective of high output power from CRM devices directly depends on the feasibility of increasing the current of helical electron beams used in these devices. However, space-charge effects begin to play a significant role with currents above 0.1 of the diode Langmuir current. These effects degrade the beam parameters primarily by increasing the oscillator velocity spread and reducing the average oscillator velocity [65]. Thus, the increased oscillator velocity spread due to space charge is the main factor limiting the current of helical electron beams in CRM devices [66].

Tsimring proposed to mitigate this factor and increase the electron beam current in CRM devices by two approaches. One was to optimize the electrode geometry and magnetic field distribution [66, 67], and the other was to utilize ion neutralization of helical electron beams. He regarded the latter as a means of improving beam quality (in

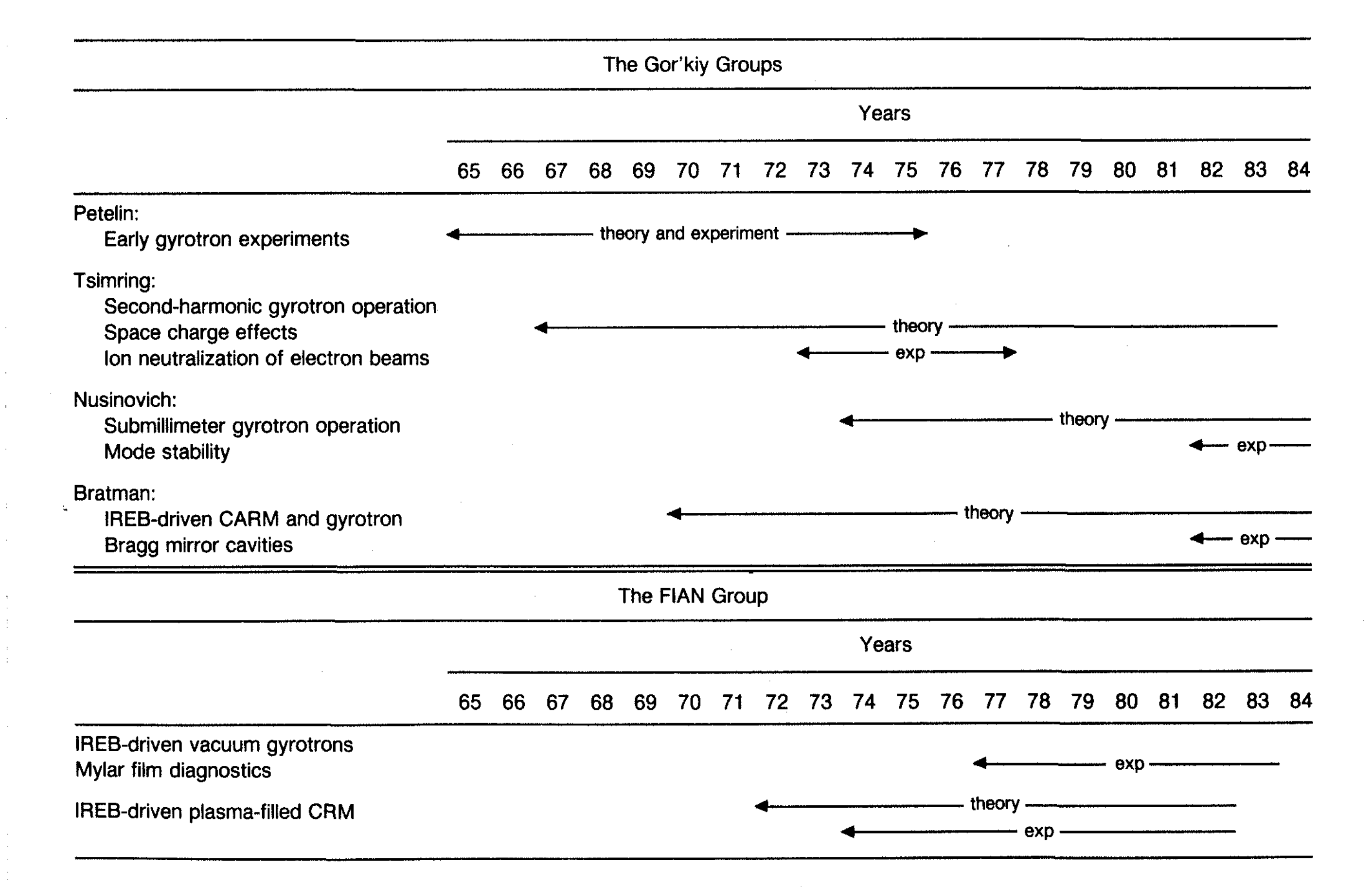


Fig. 1—Chronology of main CRM-gyrotron R&D groups

particular, decreasing the velocity spread) and increasing beam current limit, and as a unique diagnostic method for the general study of space-charge effects on helical beam parameters [65].

In the attempts to optimize the electrode geometry, the non-adiabatic distribution of the space charge precluded the use of standard analytic methods and left numerical trajectory analysis as the only means of determining the details of the mechanism according to which space charge induced velocity spread. The computer algorithm must be applicable to long beams in which the distance from the cathode to the boundary of the beam-formation region exceeded by more than an order of magnitude the average pitch of the helical trajectory.

However, the analysis of space-charge effects in long helical electron beams turned out to be a complex problem. Numerical trajectory analysis required considerable computer time, estimated approximately as a quadratic function of the beam length, and could exhaust the operational memory limits of such computer types as the M-220 and the BESM-6. Tsimring suggested that a considerable machine-time economy could be achieved by the method of auxiliary charges, in which the charge density distribution on the electrodes is approximated by virtual ring charges postulated behind the electrodes. When integrating equations of motion, machine-time could also be saved by recourse to a rectangular grid (method of grids) mapped onto the electron beam. According to this method, the surface and volume charge potentials are first computed for the grid nodes, while the electric-field components at trajectory points are then found by interpolation. The process of interpolation also plays the role of an averaging algorithm that decreases the errors due to the quantization of the space charge [66, 68].

Tsimring's trajectory analysis employed the solution of a system of equations of motion, and Poisson's and continuity equations for the case of axial symmetry typical of CRM.

The results were used to determine the electrode configuration of the electron gun forming a quasi-laminar helical beam with significantly reduced oscillator velocity spread. The analysis has also verified the hypothesis that the mechanism of velocity spread with increased current of helical beams is basically associated with resonance deceleration or acceleration of electrons in the region of regular intersection of electronic trajectories [66].

In a subsequent paper, Tsimring has introduced an algorithm utilizing the method of auxiliary charges and expanding the method of grids to a potential grid and two space-charge grids, one of which significantly facilitated the computation of far-field beam charges. Tsimring's method was found effective in the design of high-perveance helical beam formation systems [68].

The results of experiments with ion neutralization showed that it can practically fully restore to high-current beams the values of oscillator velocity spread and average oscillator velocity that are typical of low-current beams [65, 69].

Tsimring's electron beam trajectory analysis of relativistic CRM also showed that the relativistic velocity dependence of mass significantly changes the average electron oscillator velocity and weakly affects the velocity spread. Graphs were provided to make corrections to the nonrelativistic adiabatic theory of CRM electron guns [70].

Tsimring's early experiments involved a gyrotron with a special shape of cavity to provide for an axial distribution of the rf field approximating an unsymmetrical triangle. According to Gaponov (1967) and Moiseyev (1968), such a distribution can, in principle, allow for efficiencies as high as 65 to 70 percent. The shape of the resonator cavity necessary for the desired axial distribution of the rf field had, at first, been evolved analytically and further refined by numerical methods.

The stability of the solenoid current was enhanced by a transistorized stabilizer that decreased magnetic field pulsations to the level of 0.03 percent. The following were the experimental parameters for second-harmonic mode with a magnetic field of 6 kG and cavity Q of 4000: In the cw regime, the electron beam energy was 19 keV, maximum current 2 A, efficiency 41 percent at 1 A, output power 10 kW, and output wavelength 8.9 mm in the TE_{021} mode. In the pulsed regime, peak cathode voltage was 26 kV, peak current 10 A, pulselength 5 μsec, pulsed repetition rate 400 Hz, output power 30 kW with a 3 A current, and efficiency 43 percent. A combined power supply system was used, in which high-voltage pulses were supplied to the anode/first-cathode gap, and dc voltage to the first-cathode/resonant-cavity gap [25].

In subsequent experiments with the same gyrotron, the beam current was increased to 14 A and parasitic modes were suppressed with an absorber in the form of a graphite-coated quartz cylinder. The output power was 120 kW at the output wavelength of 8.9 mm in the TE_{021} mode and efficiency of 23 percent [32].

No further experiments by this group were found in the publications after 1977.

Nusinovich's Group

Nusinovich's group has been active since 1974 in theoretical work, and since 1982 has performed a number of experiments, specializing in studies of mode stability in high-power, large-cavity gyrotrons.

Experimental devices included a submillimeter gyrotron (100 kW at 0.6 mm).

The group includes V. A. Flyagin, A. G. Luchinin, B. V. Shishkin, O. V. Malygin, I. G. Zarnitsina, V. Ye. Zapevalov, and L. G. Blyakhman.

publications first appeared, to the present—has dealt with problems of mode stability in gyrotrons. A constant objective stated in many of its papers was a higher output power achieved by increasing the cavity volume and the solution of the attendant problems of mode competition [46, 71–73]. The analysis was attempted to determine optimum conditions for single-mode operation, or a particular microwave output power level within a given frequency range [72], and included mode stability in operation at the second harmonic frequency [74].

The group's experimental work, reported in published literature since 1982, has been limited to one gyrotron prototype and its application. The avowed objective of this work was a breakthrough into the submillimeter gyrotron operating range. The main problem in reaching that range, according to Nusinovich, involved the generation of a sufficiently strong magnetic field. The conventional method of producing such fields, based on superconducting solenoids, was limited to field intensities of 100 to 150 kGauss; as a result, the shortest wavelength obtained in a superconducting-solenoid gyrotron was 0.92 mm, as reported by Zaytsev [26]. Therefore, Nusinovich based his submillimeter wavelength gyrotron experiments on pulsed magnetic fields that are expected to reach 250 to 300 kGauss, rather than on superconducting solenoids [3].

In order to minimize the necessary volume of the magnetic field, the 2.4 mm copper wire for the pulsed solenoid was wound directly on the 1 mm stainless steel gyrotron cavity wall. The solenoid was installed in two sections separated by a 5 mm gap, ensuring field homogeneity better than 0.1 percent over a 10 mm path. The solenoid was driven by a 5 kA current. The magnetic field with a 5 msec pulselength had a pulse-to-pulse stability of up to 0.1 percent and reached 240 kGauss in test runs. The pulselength of the magnetic field was based on the consideration that the skin effect of the thin metal wall of the gyrotron would screen off alternating magnetic fields shorter than 1 msec. The solenoid was cooled with liquid nitrogen and withstood several thousand pulses without deterioration.

The gyrotron was operated up to 70 kV and 20 A, with the magnetic field ranging from 140 to 220 kGauss. The maximum output power was 120 kW for 66 kV, 12 A and 150 kGauss, corresponding to an efficiency of 15 percent. The operating wavelength was 0.8 mm with a pulselength of 80 μsec. For the wavelength of 0.71 mm, the output

power reached 80 kW. A shorter cavity produced 100 kW with an efficiency of 8.2 percent at the wavelength of 0.6 mm [9].

The gyrotron was intended for use in plasma diagnostics [3, 9]. In connection with this application, Nusinovich measured the spectral composition of the gyrotron output. In two experimental series, the gyrotron operated at the wavelengths of 4 and 3.2 mm. In the first series, the magnetic field pulse had a close to sinusoidal shape and a 10 msec pulselength. The following were the operating parameters of the device: For an input of 50 kV and 9 A, the 4 mm output power was 156 kW with an efficiency of 34.6 percent. For 60 kV and 19 A, the power output was 212 kW and efficiency was 19 percent. At a higher magnetic field intensity, another mode was obtained with an output wavelength of 3.2 mm. For 60 kV and 20 A, the output power was 300 kW with 25 percent efficiency.

In the second series of experiments, the magnetic field pulse had a flat 3 msec segment. The high-voltage pulse was timed to coincide with points of the flat segment of the magnetic field. When the timing was shifted within a 2 msec range, the power and efficiency of the 4 mm wavelength output remained practically constant, indicating the feasibility of gyrotrons with microwave pulselength comparable to the magnetic field pulselength. The results of the experiments showed that the main lobe of the output radiation had a width of less than 1 MHz [53].

Bratman's Group

Bratman's group specializing in IREB-driven CRM and gyrotron oscillators, has been engaged in this research at least since 1970 in theoretical analysis, and since 1982 in experimental work. It has been responsible for the development of millimeter wavelength gyrotrons capable of mode selection and high current transport. Experimental devices include a high-current gyrotron with echelette TM mode cavity (30 MW at 2.8 mm), and a CARM with Bragg mirrors (10 MW at 2.4 mm). Its electron beam facility has been the Neptun-2 accelerator delivering a hollow electron beam with 500 to 600 keV, 0.5 to 7 kA, and 100 nsec pulselength.

The members of this group include G. G. Denisov, A. B. Volkov, I. Ye. Botvinnik, M. M. Ofitserov, A. Sh. Fiks, B. D. Kolchugin, M. D. Tokman, and N. S. Ginzburg.

Gyrotron research publications of this group began appearing in the early 1970s when they were mainly concerned with theory. The objective was to optimize gyrotron parameters. Thus, for a given current, Bratman determined the length, L, of the homogeneous magnetic field

region associated with maximum efficiency. He found that efficiency to reach 60 percent and to decrease slowly with increasing current and decreasing length of the system. The output power was found to be proportional to $(L/\lambda)^{-3}$ [75].

An early experimental report, coauthored by M. M. Ofitserov associated with Bratman's current experimental group, described a mm wavelength gyrotron featuring a selective quasi-optical cavity and a diffraction-type energy extraction. The following experimental parameters were reported: Pulsed magnetic field of 200 kG and 500 μsec pulselength, stainless steel cavity with Q = 400, electron beam voltage of 35 kV, current of 5 A, voltage pulselength of 3.5 μsec, output wavelength from 2.2 to 1.2 mm, output power of 10 to 20 kW, and efficiency of 10 percent [33].

Bratman's series of high-current, relativistic electron-beam experiments has been reported in the literature since 1982, following the publication of Strelkov's series of gyrotron experiments [4, 40] described below (see "The FIAN Group: Vacuum devices"). The latter was considered by Bratman to be the first successful experimental effort with relativistic gyrotrons, although it demonstrated dramatically the basic problem of maintaining high currents together with single-mode generation. Early solutions of this problem involved slightly degrading the selective properties of the cavities and decreasing efficiency in order to reduce the diffraction Q-factor and to increase the current significantly. More recently, coupled mode-transformer cavities were successfully used for this purpose. A new approach to this problem has been proposed in the form of an axially symmetric, echelette-type cavity for the TM mode.

Bratman noted that, so far, all gyrotrons utilized TE modes, which bunched electrons more effectively than TM modes and required lower starting currents. The use of the TM modes can be advantageous if the Q-factor of the TM mode is only a few times higher than that of the TE mode. This can be achieved in the echelette TM mode cavity. The echelette is a conical structure with a stepped internal surface. Since in IREB-driven oscillators the cavity must allow the electron beam to propagate close to metal surfaces, the echelette cavity features an internal coaxial rod. Azimuthal mode selection in such a cavity is accomplished with the aid of wide azimuthal cuts in the echelette.

The gyrotron was driven by the Neptun-2 accelerator delivering a hollow electron beam with 500 to 600 keV, 0.5 to 7 kA, and 100 nsec pulselength. Transverse velocity was imparted to the electrons in a short waveguide section with two copper rings with radial cuts in a relatively weak magnetic field of 10 to 20 kGauss. The transverse velocity was then increased in a magnetic field adiabatically increasing

to 40 to 70 kGauss. In a cavity with Q of 400, a maximum output power of 20 to 30 MW was observed at a wavelength of 4.0 mm with an electron beam current of 2 kA and efficiency of 3 percent. In a cavity with Q of 100, the output power of 20 to 30 MW was reached with a current of 6 to 7 kA and efficiency of 1 percent at a wavelength of 2.8 mm [39].

In another series of experiments, Bratman's group investigated the cyclotron autoresonance maser (CARM) which is based on a quasi-axial electron radiation, rather than the quasi-transverse radiation typical of the gyrotron. In their 1982 report [59], Bratman's group viewed the CARM as a variant of a free-electron maser whose electrodynamic structure could be made to operate either as a CARM or as a ubitron, depending upon the method of magnetic field modulation. The cavity of the device was a quasi-optical resonator featuring Bragg mirrors. The objective of the design was to ensure mode selection and high current transport simultaneously.

The hollow electron beam had the following parameters: 350 to 600 keV, 0.4–1.0 kA, 100 nsec pulselength, and 6 mm diameter. A double cathode immersed in a magnetic field of the same intensity as the interaction region field minimized the spread of the transverse velocity and the electron guiding center radii. The spatial modulation of the magnetic field with a 2 cm period was accomplished by having the field of a pulsed solenoid displaced by a system of copper rings with radial slits, the latter serving to prevent a decrease in the axial field. Three such rings were used in the CARM regime, and 12 in the ubitron regime. The cavity was a circular cylinder with end corrugations representing the Bragg mirrors. The working mode was TE_{11} with phase velocity of 0.97c. The coefficient of reflection from the mirrors was 0.9.

A well-reproducible, single-mode generation was obtained at a wavelength of 4.3 mm. In the CARM regime, the output power was 6 MW with an efficiency of 4 percent (6 percent after allowing for the cavity wall loss). The frequency conversion was 3 to 4.

In a subsequent experiment with this CARM, Bratman used a higher-order mode, the TE_{41}, to shorten the wavelength and increase the output power.

The Neptun-2 accelerator provided an electron beam with 500–600 keV, 0.3–1.5 kA, and 100 nsec wavelength. The periodic magnetic field of 20 kG was displaced by the three rings spaced at the Larmor distance from one another. By shifting the timing of the electron pulse in relation to the magnetic field pulse, it was possible to control the electron rotational velocity within the limits from $\beta = 0.2$ to $\beta = 0.4$. The initial transverse velocity spread was less than 0.05. The diffraction

and ohmic Q factors of the TE_{41} mode were 3000 and 1000 respectively. The observed starting current was 500 A for $\beta = 0.2$.

The CARM provided a stable generation with an output power of 10 MW at a wavelength of 2.4 mm, efficiency of 2 percent, and pulse-length of 20 to 30 nsec [60].

THE FIAN GROUP

Vacuum Devices

The vacuum-gyrotron subgroup was publishing at least by 1977 and was entirely dedicated to experimentation. It is credited with the first successful experiments with relativistic gyrotrons. Its development of special electron-beam and microwave diagnostic systems using mylar film luminescence made it possible to measure directly the radius and angular dispersion of the electron beam and the spatial distribution of the radiated mode. Experimental devices included a quasi-optical cavity gyrotron (23 MW at 7.5 mm).

The Terek-2 accelerator, 400 keV, 1 kA, 30 nsec pulselength, was the electron-beam facility serving both vacuum and plasma-filled devices.

The membership of the subgroup includes, beside Strelkov and Krementsov, A. G. Shkvarunets, Ye. A. Vinogradov, V. I. Golovanov, N. A. Irisova, V. V. Bogdanov, V. Yu. Shafer, N. S. Ginzburg, P. Shunka, and the technicians A. V. Chirkov, V. P. Markov, and S. N. Voronkov.

In 1978, Strelkov submitted a report on a 3 cm IREB-driven gyrotron which delivered 25 MW output power with a 20 percent efficiency. Stressing the need to go over to high-current relativistic electron beams in order to increase gyrotron power, Strelkov noted that "At the present time, highly efficient gyrotrons with weakly relativistic beams have been built . . .," referring to Zaytsev's 1974 publication (submitted in 1973) as an example. It is likely, therefore, that Strelkov's 25 MW gyrotron was completed well before the 1978 submission date [4].

In the transition to IREB-driven gyrotrons, Strelkov's main problem appeared to be the formation of beams with a sufficiently high pitch whereby the transverse component of beam electron velocity would be of the same order of magnitude as the axial component. The theory supporting this experiment has been developed by Bratman, Ginzburg, and Nusinovich [54].

The electron beam from the Terek-2 accelerator had up to 400 keV, 1 kA, and 30 nsec pulselength. The pulsed magnetic field was 10

kGauss and 2.5 msec at both ends of the cavity region where the field was homogeneous with an accuracy of 2 percent. Since the accelerator diode was situated inside a massive stainless steel block, the magnetic field was slower to reach the diode region than the cavity center. This made it possible to vary the ratio of magnetic field intensity in the center to that in the diode from 5.5 to 1.3 by varying the delay between the magnetic field turn-on and the high voltage pulse from 1.0 to 2.2 msec. A 50-percent-transparent stainless steel mesh covered the anode slot facing the cathode, on the cathode side, to improve the homogeneity of the electric field. Additional mesh sheets outside the anode were used to reduce the injection current. The electrons were injected into the drift space at an angle of 30°. The generated mode was TE_{13}. The generation threshold of the gyrotron was 100 A. The current of 400 A marked maximum efficiency of 20 percent and peak output power of 25 MW. Further increases in current decreased efficiency without affecting peak power. The power saturation with increasing current was attributed to the space charge, which decreased electron energy and increased the energy spread of the beam. Strelkov expected that externally generated plasma to neutralize the space charge would significantly improve beam quality and increase current and output power [4].

In 1981, Strelkov employed the non-adiabatic magnetron injector to produce an IREB of high quality whose beam current was equal to the total current generated in the diode [10, 40]. The most important difference between this development and Strelkov's previous work on 3 cm gyrotron [4] was the new feasibility to measure the beam radius and the angular dispersion for each shot of the accelerator [48]. The spatial distribution of the radiated mode of a single pulse from the 25 MW 20 nsec gyrotron has thus been determined for the first time in this experiment [10].

The beam diagnostics system employed in the experiment was based on photographs of mylar film luminescence integrated over an electron beam pulse and representing current density distribution in a given beam cross-section. As noted above (see "Diagnostics of IREB and Microwave Output Radiation"), this system was developed in a series of previous experiments of this group [63].

The gyrotron was driven by an IREB from the Terek-2 accelerator and delivered a pulse of 0.3 J with a peak power density in the observation plane of 4.5 MW/cm^2 at a wavelength of 7.5 mm in the TE_{13} mode. The diagnostic mylar film was metallized on the diode side and served as one of the cavity mirrors. This made it possible to use a beam with radius close to that of the cavity and thus to increase the limiting current passing through the cavity. The cavity-to-waveguide

matching stub served as the other mirror. The peak power output of the gyrotron was 30 to 40 MW, as computed from air breakdown data for the observed spark in front of the antenna horn, and 23 MW as measured with a semiconductor detector. At peak power, the beam energy was 380 keV, current 1.3 kA, pulselength 20 nsec, magnetic field about 19 kGauss, and efficiency about 5 percent [40].

The new features of the diode were the capability to vary beam diameter within a relatively broad range without significant change of the Larmor radius and low angular velocity spread. Another departure from the previous 3 cm experiment was that the beam was maximally compressed to the walls of the cavity and injected so that its radius corresponded to the third maximum of the electric field of the TE_{13} mode in the cavity. The beam diameter in the cavity and its pitch were varied by varying the cathode radius and the ratio of the diode and main magnetic fields [6].

The experiment demonstrated the capability of high-current accelerator diodes to form hollow beams with high transverse electron velocities and low angular divergence. It has also demonstrated that output power was strongly dependent on the geometry of magnetic field used to shape the beam. The cause of this dependence was not known.

Plasma-Filled Devices

The subgroup working on plasma-filled gyrotrons includes, besides Rabinovich, Rukhadze, Strelkov, and Krementsov, L. S. Bogdankevich, A. G. Shkvarunets, M. V. Kuzelev, D. S. Filippychev, Ye. V. Liperovskaya, F. Kh. Mukhametzyanov, and O. D. Klok. S. N. Voronkov, A. V. Chirkov, and V. P. Markov are technicians. The Rabinovich-Rukhadze team, augmented by Bogdankevich, represents a long-standing expertise in plasma dynamics.

FIAN research on plasma-filled gyrotrons dates to at least 1972, when the basic theory was formulated. The plasma-filled gyrotron experiments were first reported in 1974. The studies include gyrotron current enhancement by beam neutralization with plasma, and the development of high-current, relativistic plasma electronics. Experimental devices have included a plasma-filled gyrotron (90 MW at 1.5 cm).

The work on plasma-filled devices is based on the claim that vacuum systems prevent the full utilization of accelerator power because of the limitations imposed by the electron space charge and magnetic self-field of the electron beam. Thus, to Rukhadze, the leading Soviet exponent of plasma electronics, the term "high-current electron beams" means, first of all, beams whose current exceeds the so-

called limiting vacuum current. Such beams can propagate in waveguides only if the electron space charge is neutralized by plasma whose density is higher than that of the beam itself. Therefore, Rukhadze maintains that, strictly speaking, high-current microwave electronics can only be plasma electronics [76].

In vacuum devices, as the beam current approaches the critical current level, the total magnetic field of the system becomes inhomogeneous across the beam, increasing the energy spread of the beam, with only a small portion of electrons participating in the resonant interaction. This degrades the efficiency and power of both Cherenkov and CRM oscillators that depend on the condition of resonance of the beam and the field. Therefore, vacuum microwave devices are efficient only if the beam current is very much lower than the critical current. The presence of plasma eliminates these limitations. The neutralization of the electron beam charge and the equalization of electron energy over the entire beam cross-section, so that all electrons participate in the excitation of the cyclotron wave, are responsible for the considerable increase of power output in plasma as compared with a vacuum environment. Furthermore, plasma oscillators are expected to be readily tunable by varying plasma density [77–79].

IREB currents of practically any size can be injected into plasma. This is the main advantage of plasma electronics, since modern high-current accelerators possess practically inexhaustible current resources [37].

The plasma filling the electrodynamic system should be thin enough to avoid affecting the system frequency and shielding the generated output radiation. At the same time, it should be dense enough to neutralize beam space charge and current. The following are some basic relationships governing plasma parameters. Beam charge and current neutralization requires that plasma density be larger than electron density in the beam. Transmission of output radiation requires that plasma frequency be lower than generation frequency. To prevent generation by plasma itself, the plasma frequency,

$$\omega_p < 2.4\, v\gamma$$

where v is electron velocity and γ is the relativistic factor. For the fundamental radial mode, the power of a plasma-filled CRM or gyrotron oscillator can theoretically exceed that of its vacuum analog by a factor of 20. Rukhadze obtained the value of 2 GW for the theoretical optimal output power of the vacuum CRM, assuming a 3 MeV, 8 kA electron current and fundamental frequency [15, 47].

A dense enough plasma will not only neutralize the beam space charge, but will also affect the electrodynamics of the resonator cavity and, particularly, its natural frequencies. The dense plasma will thus itself serve as the electrodynamic system in which the electron beam excites electromagnetic waves. Such a plasma defines the field of "pure" plasma electronics which will make it possible to use electron beam currents many times higher than the limiting vacuum current and to achieve efficient generation of wavelengths much shorter than the transverse dimension of the cavity. Plasma microwave electronics is thus the means of creating efficient high-frequency, high-power sources of electromagnetic radiation. Systematic experimentation with pure plasma oscillators based on plasma wave excitation and using relativistic electron beams has not yet been attempted.

The theory of plasma electronics is based on analogy with the theory of plasma instabilities. It requires one to determine the conditions promoting instability, the frequencies of electromagnetic waves excited by the beam, their growth rates, the electron beam starting currents, the nonlinear stage of instability saturation, and the oscillator efficiency [76].

Early results of experiments with plasma-filled devices showed that the radiated power increased by almost two orders of magnitude with increasing plasma density, as compared with radiation generated in vacuum.

According to a 1979 estimate, the efficiency of relativistic microwave vacuum oscillators was 0.2 to 0.3 and was expected to reach 0.5 to 0.6 in the near future. The range of beam energy was 0.5 to 1.5 MeV and could be expected to reach 3 to 4 MeV, although not without overcoming considerable technical difficulties. Soviet researchers noted that in the 1973 and 1974 experiments with high-power Cherenkov microwave experiments, the beam current of about 4 to 5 kA had almost reached its theoretical limit of their electrodynamic systems: At maximum power, the beam current slightly exceeded one-half of the vacuum current limit. In 1975, Friedman in the United States achieved an even more efficient generation from the Cherenkov mechanism, reaching an output power of 6 MW at a wavelength of 10 cm and 20 percent efficiency. That experiment, too, was driven nearly to its theoretical limit.

Since, according to the above accounts, vacuum cyclotron resonance masers and Cherenkov devices have already come close to their theoretical limits, the development of plasma analogs of these devices is seen by Soviet researchers as the logical next step on the way to increased power [37]. A new research objective to generate electromagnetic waves from IREB-plasma interaction has been formulated [77].

However, the creation of plasma sources of coherent electromagnetic radiation became a realistic objective only during the past decade, thanks to new developments in technology and in the physics of IREB. Although at this time only the first successful steps have been taken towards the construction of plasma amplifiers and oscillators, their theory has been basically already developed: One could say that the theoretical foundation of a new chapter of plasma physics—high-current relativistic microwave plasma electronics—has now been established [76].

Soviet authors date the interest in plasma oscillators to 1949 theoretical papers by A. I. Akhiezer and Ya. B. Faynberg in the USSR and D. Bohm and E. Gross in the United States, who discovered two-stream beam-plasma instability. The realization of the plasma microwave oscillator became possible after theoretical and experimental studies of two-stream instability and the development of a general theory of plasma microwave oscillators [78].

Microwave plasma electronics was founded by Ya. B. Faynberg, of the Khar'kov Physico-technical Institute (KhFTI), who discovered two-stream instability and performed the first experiments in exciting plasma oscillations by an electron beam [37]. A general theory of the plasma oscillator was presented by Bogdankevich, Kuzelev, and Rukhadze [76]. According to Rukhadze, the currently developed methods of analyzing spatially limited beam-plasma systems are inadequate for handling the general case of arbitrary beam density. At this time it is possible merely to consider beam currents slightly higher than the limiting vacuum current and only the linear terms of current density expansion.

Rukhadze developed in detail the linear theory of plasma oscillators and applied it to specific types of plasma microwave oscillators, including TE and TM mode cyclotron resonance masers, low-frequency TM-mode Cherenkov plasma oscillators, and a Cherenkov oscillator with weakly corrugated slow-wave structure. The nonlinear theory was applied to the case of the Cherenkov mechanism of two-stream instability when an axial monoenergetic hollow electron beam interacts with an axially-symmetric plasma TM mode in a smooth metal plasma-filled waveguide immersed in a strong axial magnetic field. These applications are claimed to represent the current state of the art in the theory of plasma microwave electronics [76].

In gyrotrons, the limiting current increases fairly slowly with beam energy, reaching only 10 kA at 3 MeV. Consequently, the power of vacuum gyrotrons is limited; for example, for a 1 MeV beam, the maximum theoretical power of a high-efficiency (30 percent) gyrotron is 1.5 GW. The limiting current of Cherenkov oscillators is much higher and

their maximum theoretical power reaches 5 GW, given the same parameters of 30 percent efficiency and 1 MeV beam. Plasma-filled gyrotrons double their limiting current, while plasma-filled Cherenkov oscillators may have their limiting current increased as high as six times over vacuum conditions, for beam energy of 3 MeV. The Cherenkov oscillator thus appears superior to the gyrotron in terms of theoretical power output. However, the advantage of gyrotrons is that the dimensions of their electrodynamic systems may be many times the wavelength, a significant factor in the millimeter wavelength range. In practice, therefore, for the same wavelength, gyrotrons can tolerate much higher currents than Cherenkov oscillators [37].

The first experiments with plasma-filled IREB-driven microwave oscillators were performed in 1972 by Yu. V. Tkach of KhFTI, who studied the Cherenkov interaction regime in an iris-loaded waveguide. Using a 1 MeV, 60 kA, 30 nsec pulselength electron beam, and nitrogen plasma with density of up to 10^{13} cm^{-3} in the waveguide, Tkach observed a microwave power output of 10 MW at a frequency of 2.6 GHz [80].

In the next series of experiments, reported in 1975, Tkach compared microwave generation using a slow-wave structure in vacuum and in plasma. With the same electron beam as above, the vacuum system limited the beam current to 12 kA. The observed output power was 200 to 300 MW with a 15 to 20 nsec pulselength. In the plasma-interaction experiment, an electron beam with a current of 20 to 22 kA was injected into a waveguide filled with gas to a pressure that could be varied from 10^{-5} to 5.0 Torr. Generation at the 3 cm wavelength reached the power of 600 MW, exceeding vacuum power by a factor of 2 to 3 [81].

By 1979, Tkach demonstrated a strong dependence of output power on gas pressure: from 200 to 300 MW for 10^{-4} Torr (vacuum regime) to 700 MW for 10^{-2} Torr. Tkach used a corrugated waveguide designed for the wavelength of 3.3 cm and an electron beam of 700 keV, 5 kA, and 30 nsec pulselength. At maximum power, the injection current was 4 to 5 kA and efficiency was 22 percent. These results were attributed to the formation of plasma in the electrodynamic system of the oscillator, which neutralized the beam charge and improved the beam-propagation conditions in the system. Above 10^{-2} Torr, generation ceased, apparently due to shielding of the output radiation by the dense plasma [37].

Parallel experiments with microwave generation in plasma-filled waveguides were performed by P. S. Strelkov and his group at FIAN, who studied cyclotron resonance masers and gyrotrons. Strelkov used a smooth waveguide partially filled with externally generated plasma

whose density could be varied from 10^9 to 10^{13} cm^{-3}. Strelkov's first plasma experiment, reported in 1975, yielded the following results [77]:

Electron beam, Terek-2 accelerator:

Voltage	350 keV
Current	1.5 kA
Pulselength	35 nsec

Resonant cavity:

Metal waveguide, smooth, 15 cm in diameter, 120 cm long

Plasma region:

Xenon plasma generated by auxiliary 1 keV, 1 A, 100 μsec electron beam

Density $10^9 - 10^{13}$ cm^{-3}

Magnetic guide field: 4.8 kG

Microwave output:

Wavelength 3 cm

Titanium foil, 50 μ, scattering angle 48°, beam transverse energy equals axial energy

Power, 2 MW at plasma density of 5×10^{12} cm^{-3}

Aluminum foil, 10 μ, scattering angle 10°, beam transverse energy equals 0.03 of axial energy

Power, 20 kW at plasma density of 2×10^{10} cm^{-3}

As plasma density increased, the radiated power increased by a factor of 30 to 40 compared with radiation from a vacuum waveguide, although the current rose by a factor of only 2 to 3. At very high plasma densities, the radiation was screened off. The experiment was designed for optimum generation without regard to efficiency, which was only 1 to 2 percent at maximum power. The experiment showed that the shortwave radiation represented stimulated cyclotron radiation from the beam electrons. No other radiation mode was observed at maximum power in plasma.

The considerable increase of the power output in the plasma environment as compared with a vacuum regime was regarded as the most important result of the experiment [77].

The above experiment was a preliminary attempt to study cyclotron radiation from relativistic electrons in plasma-filled electrodynamic systems. Nevertheless, it was considered a proof of the feasibility of exciting intense radiation in plasma and developing a single-mode

plasma microwave oscillator driven by an IREB [41, 78].

Strelkov's next attempt, reported in 1978, represented the realization of a plasma-filled gyrotron with a supercritical electron current [47]. It yielded these results:

Electron beam, Terek-2 accelerator:

Voltage	320 keV
Current	1.2 kA
Pulselength	30 nsec

Resonant cavity:

Used in previous vacuum gyrotron experiments, designed for the TE_{13} mode

Plasma region:

Xenon plasma generated by auxiliary 2 keV, 1 A, 20 μsec electron beam
Plasma density from 10^{10} to 10^{12} cm^{-3}

Magnetic guide field: 5.5 kG

Microwave output:

Wavelength	3 cm
Power	60 MW at plasma density of 2×10^{11} cm^{-3}
Efficiency	15 percent

The maximum output power was found to depend on plasma density. As plasma density rose from near-vacuum to 2×10^{11} cm^{-3}, the microwave power increased by a factor of 10. Beam current in near-vacuum was 640 A, rising to 1.2 kA at plasma density of 2×10^{11} cm^{-3} [47].

At the same time, the group had performed a direct comparison between a vacuum and plasma-filled gyrotron operation [5]. A 3 cm gyrotron was excited by a 350 keV hollow beam with current variable to several kA and 35 nsec pulselength. In the vacuum regime, a maximum efficiency of 20 percent was reached at an injection angle of 45° and 0.5 kA, producing an output power of 25 MW.

Further increase in injection current in the vacuum gyrotron decreased efficiency without affecting power. However, plasma filling made it possible to increase the electron current together with output power. For each value of beam current, the oscillator operation was optimized by selecting appropriate magnetic field intensity and injection angle, and leaving the oscillation mode and wavelength unchanged. In this manner, it was possible to bring beam current up to 1.5 kA, exceeding the vacuum current limit by better than a factor of 1.5, and

reaching a power output of 65 to 70 MW at the same efficiency of 20 percent.

The authors noted that the above gyrotron with plasma filling was the first oscillator ever to operate stably and efficiently with a supercritical current and, in this sense, had no analog in vacuum electronics [5].

The most recent plasma experiment of the FIAN group, reported in 1982, dealt with particular problems left unsolved by the theory, such as the selection of optimal parameters of plasma and beam, matching of the plasma resonator to the antenna, etc. These problems were analyzed in terms of the following experimental plasma microwave system [41, 78]:

Electron beam, Terek-2 accelerator:

Voltage	480 keV
Current	0.9 kA
Pulselength	45 nsec

Resonant cavity:

Metal waveguide, smooth, 29 cm in diameter, 30 cm long

Plasma region:

Krypton plasma generated by auxiliary 1.5 keV, 10 A electron beam

Density $10^{13}-2 \times 10^{14}$ cm^{-3}

Magnetic guide field: 30 kGauss

Microwave output:

Wavelength	1.5 to 4.6 cm
Power	90 MW
Efficiency	21%

The entire experiment was performed at a single subcritical value of current where it was independent of plasma density. The experiment was designed to provide data in two areas [41, 78]:

1. Generation conditions
   - Extraction of radiation from cavity
   - Magnetic field and plasma density ranges
   - Initial angular beam divergence
   - Cavity length
2. Microwave radiation parameters
   - Frequency spectrum
   - Modes
   - Absolute power values

Rukhadze noted in 1979 that very little research in plasma electronics had been performed so far. The experiments with plasma oscillators were limited in the sense that plasma was used merely to neutralize the beam charge and thus to increase the current. There were no published reports on true IREB-driven plasma oscillators in which the radiation spectrum would be significantly determined by plasma. There are general theoretical papers on this problem, such as that by B. A. Aronov et al. [82], but they do not appear convincing enough to warrant experimental effort. The lack of adequate experimental data inhibits a thorough analysis of plasma oscillators. Rukhadze estimated that such oscillators would require beam energy greater than 1.5 MeV and that this requirement might well be the main obstacle to the realization of true plasma microwave oscillators [37].

THE MOSCOW STATE UNIVERSITY GROUP

A group in the Physics Department of Moscow State University, including A. F. Aleksandrov, S. Yu. Galuzo, and V. I. Kanavets, has been experimenting with a hybrid system of a relativistic CRM and an autoresonant synchrotron maser.

The hybrid system was based on stimulated resonance scattering that delivered 20 MW at a wavelength of 4 to 6 mm [83]. Like all the preceding Soviet groups, the MGU group had heretofore been primarily pursuing research on relativistic Cherenkov microwave oscillators.

Since the stimulated resonance scattering mechanism requires very-high-quality helical beams with minimal energy spread, the MGU group employed a system that combines the properties of a relativistic CRM, oscillating at the cyclotron frequency, and of an autoresonant electron synchrotron maser that amplifies electromagnetic waves at a Doppler-shifted frequency. The experimental device consists of three sections. The first is a waveguide with a magnetostatic periodic field which focuses a thin hollow electron beam and imparts cyclotron oscillations to the beam electrons. The second section is a CRM operating at the cyclotron frequency, while the helical beam in the smooth waveguide of the third section emits coherent synchrotron radiation at the Doppler up-shifted cyclotron frequency.

The experiments have been performed with the Tandem-1 pulse line accelerator of 0.4 to 0.6 MeV and 3 to 5 kA, producing a hollow electron beam 40 to 50 mm in diameter. The periodic magnetic field of the first section was established by a system of ferromagnetic rings. The microwave output consisted of two wavelengths: the cyclotron wavelength of 2.4 cm, and one of the synchrotron wavelengths of 12

and 5 mm. The output at the 5 mm wavelength exceeded significantly the emission at the other wavelengths and its power was at least 20 MW at the TE_{02} mode [83].

THE KURCHATOV ATOMIC ENERGY INSTITUTE GROUP

This group of researchers, including V. V. Alikayev, G. A. Bobrovskiy, V. V. Parail, and K. A. Razumova, studied electron cyclotron heating of plasma in the T-10 tokomak by means of the electron cyclotron resonance. In the experiments, four 200 kW gyrotrons were used, providing a total output power of 800 kW. The gyrotrons operated at a wavelength of 3.6 mm and delivered a pulselength of 0.15 sec. The magnetic systems of the gyrotrons were based on 30 kGauss superconducting magnets [88].

VII. CONCLUSIONS

High-power relativistic microwave electronics is one of the most successful areas of Soviet R&D. It has maintained a consistent record of significant achievements; it has managed to overcome the systemic weakness of the Soviet R&D system in being able to translate effectively the results of advanced research into production of practical equipment; and it has become the fastest growing area of application of pulsed power technology, which itself has been for many years the subject of priority development in the USSR.

This success story must, to a large extent, be credited to the Soviet Academy of Sciences and its research institutes, where most of the R&D process has been taking place. More specifically, however, the microwave achievement is traceable to the talent and influence of A. V. Gaponov, the director of the Applied Physics Institute in Gor'kiy, who exemplifies the paradox that, in spite of the collectivist nature of Soviet society, it is the individual who makes the difference between success and failure.

Along with his work on a broad range of high-power microwave devices, Gaponov had instituted, promoted, and pursued research on cyclotron resonance masers and gyrotrons from the inception of the idea in 1959. At that time, the research had a predominantly basic nature, which continued until 1965, the beginning of what Gaponov called the second stage of gyrotron development, and what looked like a systematic research program.

The present motivation of gyrotron research—to span the frequency gap at high power levels between the domains of lasers and conventional microwave devices—must have arisen much later, however. The basic patent disclosures of 1967 specify a broad wavelength band from centimeters to submillimeters. Gaponov's review, describing the gap in dramatic terms as a "catastrophic chasm" centered about 300 GHz, was published in 1979. In 1981, Bratman, Gaponov's collaborator at IPF, wrote that the millimeter wavelength region, probably together with a part of the submillimeter region, is the natural domain of the CRM.

Soviet publications fail to specify the particular practical applications for which the gap in frequency coverage would indeed be catastrophic. In his review, Gaponov listed several general areas in engineering and physics where the wavelength range from 0.1 to 10 mm would be of definite interest, and placed radar and communications at the top of the list. The increasing effort level, however, indicates that

Soviet CRM and gyrotron research has been pursuing a definite aim. There are about 120 names of authors and associated personnel in the literature on this research alone. While fewer than 20 such names could be accounted for in any given year before 1973, this number was double that for each year between 1973 and 1980, and rose to 78 in 1982. This peak in research personnel coincides with Bratman's experimental work on IREB-driven CARM's and gyrotrons and Nusinovich's program on submillimeter gyrotrons.

The strength of this research also derives from inter-institute cooperation. A typical Soviet applied research program is confined to a single institute, while most of the time only programs of major national importance are supported by a coordinated effort involving several research organizations. This is clearly the case with the high-power microwave program, where the tie between the Institute of Applied Physics in Gor'kiy and the Lebedev Physics Institute in Moscow proved to be especially fruitful. The program appears to include a third partner, the complex of research institutes in Tomsk. Gaponov credits it with early significant progress in accelerator development resulting in axially symmetric injectors with good shot-to-shot beam reproducibility and high pulse repetition rate. The Institute of Atmospheric Optics in Tomsk developed the Terek-2, the principal accelerator system employed at FIAN to provide a high-current relativistic electron beam in gyrotron experiments. Finally, Didenko's well-known 2 GW gyrotron experiment performed at the Nuclear Physics Institute in Tomsk provided a useful precursor for the IREB-driven gyrotron experiments in Moscow and Gor'kiy.

While we know very little about the intended end uses of the Soviet CRM and gyrotron research, there are explicit Soviet statements about the more immediate technological objectives of this research. One objective is the production of high microwave pulse energy by increasing the pulselength, average power, and cw power, in turn achieved by the development of long-service-life cathodes, heat sink collectors of electron beams, and beam extraction windows. Others are the development of high-current-density electron guns and the achievement of stable, single-mode operation of large cavities. These requirements spell out microwave devices whose high output energy is accompanied by high monochromaticity and coherence. Advanced search and pulse Doppler radars could be one application of these devices.

More distant objectives of the Soviet research are the plasma-filled gyrotrons. While plasma electronics is as yet much less developed than its vacuum counterpart, FIAN's work on IREB-driven plasma-filled gyrotrons has been proceeding at a surprisingly high level of effort, predating the vacuum research and generating more research papers by

more authors. This is probably due to the long-standing interest and involvement in plasma dynamics on the part of M. S. Rabinovich and A. A. Rukhadze, the leaders of the FIAN microwave group. The use of plasma, first conceived as a means of overcoming the limitations of high-current electron beams and later intended as a major component of high-power microwave electronics, is another avenue toward increasing microwave output energy, beyond the capabilities of vacuum electronics. FIAN's experiments have so far been confined to centimeter wavelengths, although the achieved 90 MW output power is the highest of all Soviet CRM experimental results.

The significance of the published material on Soviet CRM and gyrotron research also resides in what it should be expected to, but does not, say. There are many indications that a substantial portion of this research has been classified over the years. A general impression that this is the case is obtained from the publication pattern of the research reports in this area, showing a discrepancy between the annual publication frequencies and the number of research personnel accounted for in each year. The former shows a peak in the mid-1970s followed by a sharp drop, while the latter, as noted above, has been rising during the same period. Assuming that individual productivity averaged over the group and over time is constant, the discrepancy leaves a substantial body of papers missing from the publications after 1975 which could be attributed to classification.

It is probable that the missing literature covers at least two specific research areas: amplifiers and continuous-wave gyrotrons. Microwave research obviously must deal with amplifiers, as well as with oscillators. Nevertheless, the published material contains no technical papers on amplifier experimentation, in spite of a number of explicit indications that amplifiers were part of the experimental program.

Thus, one of the three 1967 patent applications establishing the basis of Soviet CRM and gyrotron research was dedicated to amplifier gyrotrons. Gaponov's 1980 review notes the early experiments performed with the multi-cavity gyrotron-amplifier-gyroklystron described in the patent application. Andronov's 1978 review states that by 1963, the trochotron-type amplifiers and oscillators based on the relativistic mechanism reached an efficiency of 10 percent, and that by 1967 the helical beam amplifier and oscillator delivered several kW in the X-band. In his review of plasma sources of coherent electromagnetic radiation, Rukhadze noted that by 1981 the first successful steps had been taken towards the construction of plasma amplifiers and oscillators.

Continuous-wave research is a little better represented in the published materials, but only up to 1974. The last reference to a cw experiment was published in 1978. That experiment was not attributed

to any author. Nevertheless, the cw regime has played an important role in the reviews and plans of Soviet researchers. Bratman's statement, noted above, about the CRM as a natural domain of the millimeter and submillimeter wavelength regions applied primarily to the cw regime. Gaponov's future objectives for relativistic high-frequency generators included increasing cw power. In 1973, Petelin stated that the primary objective of CRM research was the generation of wavelengths shorter than 5 mm by cw or long-pulse gyrotrons.

Another area with little or no coverage in Soviet technical publications includes the downstream stages of the R&D cycle. The sources examined for this report provide a wealth of information on the details of the theoretical and experimental process, and some data on the construction of prototypes, most of which were performed by the Academy of Sciences institutes. However, little is known about how the results of R&D have been translated into production of operational devices, what are the production rates, and what production facilities are being employed. It is possible that at least some aspects of such production are the responsibility of the Academy of Sciences.

The R&D cycle of high-power relativistic microwave devices warrants close study as a rare example of successful Soviet advanced technology. The lessons learned here may be applied to the analysis of other areas of advanced technology, providing an insight into the future capabilities of Soviet advanced technology in general.

Appendix A

PATENT TEXTS

PATENT TEXTS, GYROTRONS

A. V. Gaponov, A. L. Gol'denberg, G. N. Rapoport, and V. K. Yulpatov, NIRFI, No. 273001, priority 6-16-1967, previously not published [22].

Multicavity Cyclotron Resonance Maser

RF electromagnetic amplifier representing a two- (or multi-) cavity klystron and containing an electron source, cavities separated by drift tubes, input and output waveguides, and a solenoid to set up a magnetic field, distinguished by the fact that, to increase the cross-section and length of the interaction region for high operating frequencies, the electron source is an electron gun generating a beam of electrons moving in a magnetic field along helical trajectories and the electron rotation frequency (cyclotron frequency) or its harmonic is equal to the amplified signal frequency.

I. I. Antakov, A. V. Gaponov, V. A. Gintsburg, A. L. Gol'denberg, M. I. Petelin, and V. K. Yulpatov, NIRFI, No. 302050, priority 6-16-1967, previously not published [23].

1. **Amplifier** of electromagnetic oscillations in the centimeter, millimeter, and submillimeter wavelength ranges.

According to patent No. 273001, the amplifier is distinguished by the fact that to increase output power and efficiency, it includes an axially symmetric electron gun that forms a hollow electron beam whose radius is much larger than that of the helical electron trajectories, and the RF section, including cavities separated by operating frequency cutoff drift tubes, output cavity to output waveguide match stubs, output waveguide, and collector, is in the shape of a solid metal tube with variable internal cross-section.

2. **Amplifier** as in (1), distinguished by the fact that the mechanical cavity tuning is accomplished by having the RF section made in the shape of several coaxial metal tube lengths with variable internal cross-section capable of moving axially past each other.

3. **Amplifier** as in (1, 2), distinguished by the fact that to avoid exciting lower (with respect to the operating) modes of electromagnetic oscillations, the drift tubes contain RF radiation absorbers.

A. V. Gaponov, A. L. Gol'denberg, M. I. Petelin, and V. K. Yulpatov, NIRFI, No. 223931, priority 3-24-1967 [20].

1. **Device** to generate electromagnetic oscillations in the centimeter, millimeter, and submillimeter wavelength range, representing a cyclotron resonance maser consisting of an electron gun, cavity, collector, output waveguide, and solenoid, distinguished by the fact that to increase the efficiency and power of the device, its cavity, together with the elements matching the cavity to the output waveguide, the output waveguide, and the collector are made in the shape of a solid metal tube (waveguide) with a variable internal cross-section.

2. **Device** according to (1), distinguished by the fact that to improve the stability of the generated oscillations, the cavity and output waveguide are separated by a length of tube whose internal cross-section is smaller than those of the adjacent sections of the cavity and the output waveguide.

3. **Device** according to (1), distinguished by the fact that to increase the frequency tuning range, its cavity and output waveguide are separated by a length of metal tube whose internal cross-section smoothly increases from that of the cavity output end to that of the output waveguide.

4. **Device** according to (1–3), distinguished by the fact that its cavity has a cross-section that smoothly increases toward the collector.

5. **Device** according to (1–4), distinguished by the fact that the constant magnetic field at the cavity output end amounts to 60 to 85 percent of the magnetic field in the cavity proper.

A. L. Gol'denberg, T. B. Pankratova, and M. I. Petelin, NIRFI, No. 226044, priority 4-16-1967 [21].

Magnetron-type Electron Gun

1. Magnetron-type electron gun for cyclotron resonance masers, consisting of cylindrical anode and cathode with an emitting strip, distinguished by the fact that to generate a beam of electrons moving along helical trajectories, the diameters of the cathode, D_c, and of the electron beam, D_b, obey the relationship

$$D_c / D_b = \beta \frac{(V_c V_{ac})^{1/2}}{V_a}$$

where β is a numerical coefficient ranging from 1.7 to 2.2, V_c is the operating region potential, V_a is the anode potential, and V_{ac} is the critical voltage of the electron gun, while the cathode potential is assumed to be zero.

2. **Electron gun** according to (1) distinguished by the fact that to remove electrons with excess oscillation energy, the anode is provided with a protrusion near the outer boundary of the electron beam.

PATENT TEXTS, DIAGNOSTICS

A. P. Bazhulin, Ye. A. Vinogradov, N. A. Irisova, N. V. Mitrofanova, Yu. P. Timofeyev, S. A. Fridman, and V. V. Shchayenko, FIAN. Patent application No. 364268, 4-29-1970 [84].

1. **Receiver** for visual observation and recording of electromagnetic radiation, consisting of a receiver screen in the form of a thermo-insulating base with an absorbing metal substrate carrying a layer of thermosensistive phosphor, and an ultraviolet source exciting the phosphor, distinguished by the fact that, to increase the wavelength range, the receiver screen is made up of a set of receiving elements in a protective case with transparent windows made of plastic (mylar, for example) film stretched over clamps attached to the case. The latter has a heater with temperature control to provide the temperature corresponding to the maximum thermographic effect of the phosphor.

2. **Receiver** according to (1) above, distinguished by the fact that, to increase sensitivity, the thermo-insulating base is made in the form of synthetic film (mylar film, for example), uniformly stretched over the clamps.

3. **Receiver** according to (1) and (2) above, distinguished by the fact that, the thickness of the metal substrate is from 2 to 500 Å.

A. P. Bazhulin, Ye. A. Vinogradov, N. A. Irisova, N. V. Mitrofanova, Yu. P. Timofeyev, S. A. Fridman, and V. V. Shchayenko, FIAN. Patent application No. 371819, 8-6-1970 [87].

Receiver for visual observation and recording of electromagnetic radiation, according to patent application no. 364268, distinguished by the fact that to stabilize the characteristics and expand the operating range, the protective case is airtight and equipped with means of admitting and evacuating gases, while the windows for radiation transmission and observation of the visible image are set at the Brewster angle.

Appendix B

SOVIET CRM AND GYROTRON EXPERIMENTS

CENTIMETER WAVELENGTHS

Petelin, Gaponov, NIRFI [14]
Stimulated synchrotron emission from electrons in cavities

	Fundamental	Second Harmonic
voltage	8 kV	19 kV
current	80 mA	320 mA
wavelength	3.4 cm	1.2 cm
power	6 W	190 W

Petelin, Gaponov, NIRFI [12]
First experiments, reported in 1966
Adiabatic magnetron-type electron gun, cw operation

	Gyrotron 1 Fundamental	Gyrotron 2 Second Harmonic
voltage	20 kV	20 kV
current	0.3 A	1.4 A
wavelength	2.0 cm	1.2 cm
power	3 kW	4.3 kW
efficiency	50%	18%

Gol'denberg, Flyagin, NIRFI [85]
The experiment was reported in 1972.

voltage	40 kV
current	10 A
wavelength	cm range
power	110 kW
efficiency, max	45% at 3.5 A

Gol'denberg, Ofitserov, NIRFI [30]
The experiment was reported in 1972.
Whispering gallery mode gyrotron

voltage	40 kV
current	40 A
wavelength	2 cm
peak power	380 kW
output pulselength	3 μsec
peak efficiency	45% at 180 kW

Didenko, IYaF, Tomsk [38]
Gyrotron experiment

voltage	1.2 MV
current	8 kA
beam pulselength	60 nsec
wavelength	10 cm
power	2 GW
output pulselength	50 nsec
efficiency	30%

Krementsov, Strelkov, FIAN [77]
CRM, first plasma experiment
Electron beam, Terek-2 accelerator

voltage	350 keV
current	1.5 kA
pulselength	35 nsec
wavelength	3 cm
power	2 MW with titanium foil 20 kW with aluminum foil

Krementsov, Strelkov, FIAN [47]
Gyrotron with neutralized electron beam in plasma
Second plasma experiment
Electron beam, Terek-2 accelerator

voltage	320 kV
current	1.2 kA
beam pulselength	30 nsec
wavelength	3 cm
power	60 MW
efficiency	15%

Krementsov, Strelkov, FIAN/IPF [4, 5]
Relativistic gyrotron experiment
Microwave output, single-mode generation
Electron beam, Terek-2 accelerator

voltage	400 kV
current	1 kA
pulselength	30 nsec
wavelength	3 cm
power, max.	25 MW
efficiency, max.	20%

Strelkov, FIAN [41, 78]
CRM, third plasma experiment
Electron beam, Terek-2 accelerator

voltage	480 keV
current	0.9 kA
pulselength	45 nsec
wavelength	1.5-4.6 cm
power	90 MW
efficiency	21%

Zaytsev, IPF [86]
Two-mirror cavity with rippled walls

voltage	600 kV
current	4-6 kA
beam pulselength	80 nsec
wavelength	2.4 cm
power	300 MW
efficiency	15%

MILLIMETER WAVELENGTHS

Ofitserov, Nikolayev, NIRFI [33]
Gyrotron with adiabatic magnetron-type electron gun

voltage	35 kV
current	5 A
pulselength	3.5 μsec
wavelength	1.2-2.2 mm
power	10-20 kW
efficiency	10%

Kovalev, NIRFI [27]
Gyrotron with mode transformer, TE_{13} to TE_{11}

wavelength	5 mm
power	10 kW
pulselength	500 μsec
rep. rate	50 Hz

Tsimring, NIRFI [25]
RE 19, 782, 1974
Second harmonic operation, mm wavelength
Adiabatic magnetron-type electron gun

	cw	pulsed
voltage	19 kV	26 kV
current	2 A	10 A, peak
pulselength		5 μsec
rep. rate		400 Hz
wavelength	8.9 mm	8.9 mm
power	10 kW	30 kW
efficiency	40%	43%

Tsimring, NIRFI [32]
Second harmonic operation, mm wavelength
Same gyrotron as in [25]
Parasitic mode suppression by insert absorber in cavity

voltage	20 kV
current	14 A
wavelength	8.9 mm
power	120 kW
efficiency	23%

Krementsov, Strelkov, FIAN [6]
CRM experiments
Continuation of work reported in [4]
Electron beam, Terek-2 accelerator

voltage	400 kV
current	2 kA
beam pulselength	35 nsec
wavelength	7.5 mm
power, max.	23 MW at 1.4 kA
efficiency, max.	6% at 0.5 kA

Bratman, Petelin, Ofitserov, IPF [59]
Bragg mirror CRM

voltage	350-600 kV
current	0.4-1.0 kA
beam pulselength	100 nsec
wavelength	4.3 mm
power	6 MW
output pulselength	5-30 nsec
efficiency	4%

Bratman, Ofitserov, IPF [60]
Bragg mirror CRM
Electron beam, Neptun-2 accelerator

voltage	500-600 kV
current	0.3-1.5 kA
beam pulselength	100 nsec
wavelength	2.4 mm
power	10 MW
output pulselength	20-30 nsec
efficiency	2%

Krementsov, Strelkov, FIAN [10]
Spatial mode distribution
Electron beam, Terek-2 accelerator

wavelength	7.5 mm
power	25 MW
output pulselength	20 nsec
energy	0.3 J
power density	4.5 MW/cm^2

Krementsov, Strelkov, FIAN [40]
Gyrotron experiment

voltage	380 kV
current	500 A
wavelength	7.5 mm
power	25 MW
output pulselength	20 nsec

Nusinovich, IPF [53]
Adiabatic magnetron-type electron gun
Stabilized energy storage
Application: plasma diagnostics

	Low Magnetic Field		High Magnetic Field
voltage	50 kV	60 kV	60 kV
current	9 A	19 A	20 A
wavelength	4 mm	4 mm	3.2 mm
power	156 kW	212 kW	300 kW
output pulselength	100 μsec	100 μsec	100 μsec
efficiency	34.6%	19%	25%

Bratman, Ofitserov, Denisov, IPF [39]
Gyrotrons with coaxial echelette cavities
Electron beam, Neptun-2 accelerator

voltage	500-600 kV	
current	0.5-7 kA	
pulselength	100 nsec	
	Q=400	Q=100
wavelength	3.8 mm	2.8 and 3.4 mm
power	20-30 MW	20-30 MW
efficiency	3%	1%

Alikayev, IAE [88]
Gyrotron operational use
Application: Tokomak T-10

superconducting magnets	30 kGauss
wavelength	3.6 mm
power	200 kW
output pulselength	0.15 sec

SUBMILLIMETER WAVELENGTHS

Nusinovich, IPF [3, 9]
Sub-mm pulsed operation
Adiabatic magnetron-type electron gun
Liquid nitrogen cooling
Applications: plasma diagnostics

	Long Cavity		Short Cavity
voltage	66 kV		70 kV
current	12 A		18 A
wavelength	0.8 mm	0.71 mm	0.6 mm
power	120 kW	80 kW	100 kW
output pulselength	80 μsec		
efficiency	15%		8.2%

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FP	*Fizika plazmy*
IEEE J. Quantum Electron.	*IEEE Journal of Quantum Electronics*
IVUZ—Fizika	*Izvestiya vysshikh uchebnykh zavedeniy. Fizika*
IVUZ—Radiofizika	*Izvestiya vysshikh uchebnykh zavedeniy. Radiofizika*
JETP Lett.	*JETP Letters*
OI	*Otkrytiya izobreteniya. Promyshlennye obraztsy. Tovarnye Znaki*
Phys. Rev. Lett.	*Physical Review Letters*
PTE	*Pribory i tekhnika eksperimenta*
RE	*Radiotekhnika i elektronika*
UFN	*Uspekhi fizicheskikh nauk*
VAN SSSR	*Vestnik Akademii nauk SSSR*
ZhETF	*Zhurnal eksperimental'noy i teoreticheskoy fiziki*
ZhETFp	*Pis'ma v Zhurnal eksperimental'noy i teoreticheskoy fiziki*
ZhTF	*Zhurnal tekhnicheskoy fiziki*
ZhTFp	*Pis'ma v Zhurnal tekhnicheskoy fiziki*

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